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EFFECT OF EXTRACTIVES ON THE STRENGTH OF WOOD [1]

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INTRODUCTION

Studies of the characteristics of wood have brought to light a more or less definite relation between specific gravity and various strength properties.[4 5] The higher the specific gravity, the greater the strength; for comparison the value of specific gravity taken is that for weight oven-dry and volume at test. This relationship, however, manifests itself more as a general trend than as a perfectly uniform law, since observation early established the fact that some individual species depart markedly from average curves for a large number of species. Among the woods exceptional in these relations are many containing relatively large amounts of extractives that add materially to the weight. Some work of the Forest Products Laboratory had already shown that the amount and the character of the extractives may profoundly change other physical characteristics, and it seemed reasonable, therefore, to suppose that the relationship between specific gravity and strength might also be affected. The present study was undertaken to obtain information on the effect of extractives [6] on a limited number of important strength properties.

Redwood (*Sequoia sempervirens*), western red cedar (*Thuja plicata*), and black locust (*Robinia pseudoacacia*) were chosen for the experiments because they contain relatively large amounts of extractives. Redwood particularly has shown rather unusual moisture-strength relations, and when green is high in certain strength properties. It is therefore an especially desirable species for study. In the woods examined the high extractive concentration is confined to the heartwood, the sapwood containing only small amounts. Previous studies at the Forest Products Laboratory on the distribution of extractives in redwood had shown also that the concentration in the heartwood varies considerably with height in tree and with position in cross section of the trunk. The heartwood extractives are highest in the butt adjoining the sapwood and decrease toward the center of the

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[3] Maintained by the U. S. Department of Agriculture at Madison, Wis., in cooperation with the University of Wisconsin.

[4] NEWLIN, J. A., and WILSON, T. R. C. THE RELATION OF SHRINKAGE AND STRENGTH PROPERTIES OF WOOD TO ITS SPECIFIC GRAVITY. U. S. Dept. Agr. Bul. 676, 35 p., illus. 1919.

[5] MARKWARDT, L. J. COMPARATIVE STRENGTH PROPERTIES OF WOODS GROWN IN THE UNITED STATES. U. S. Dept. Agr. Tech. Bul. 158, 39 p. 1930.

[6] As here used, extractives are defined as the portion of the wood that will dissolve when the wood is placed in an inert solvent. They are known, for example, as cold-water, hot-water, or alcohol soluble extractives, the name depending upon the solvent used. Total extractive-content values were derived from wood that was finely ground before it was placed in the solvent.

cross section. As the height increases the heartwood extractives gradually decrease near the outside of the tree and increase near the center, so that close to the top the extractive content of the heartwood is about the same throughout the cross section. The extractive content of the sapwood is low and does not vary much throughout the height of the tree.

One inherent difficulty in investigative work like that just mentioned is that the wood put on during successive yearly growth periods may show large variations in strength, so that the best method of selecting or of matching material to eliminate this factor would be to obtain specimens, with and without extractives, from the same annual growth rings. Obviously, this desirability could not be realized, and it was necessary to resort to other methods, which will be described later.

In making comparisons between different groups of material tested, some way of evaluating the significance of extractives in terms of strength is desirable. One method is to adjust the test values for the various strength properties in accordance with the specific gravity-strength equations already determined,[7] [8] and to evaluate the effect of extractives in terms of the strength differences that should normally accompany the difference in the specific gravity observed. This method of appraising differences of weight in terms of the theoretical effect of a like amount of wood substance has been employed throughout the study.

EXPERIMENTAL WORK AND DISCUSSION OF RESULTS

SCOPE OF TESTS

Four distinct methods were used to determine the effect of extractives on strength, as follows:

(1) Sapwood, which is usually low in extractives, was compared with heartwood, which is relatively high in extractives.

(2) Redwood heartwood from which extractives were partly removed by forcing cold water through in the direction of the grain was compared with adjoining unextracted heartwood.

(3) The outer portion of a kiln-dried redwood block in which the concentration of extractives had been increased by the transfer that is normal during kiln drying was compared with an adjoining interior portion of lower extractive content.

(4) Sapwood of redwood soaked in redwood extractives was compared with normal sapwood.

COMPARISON OF SAPWOOD AND HEARTWOOD

The sapwood of redwood, western red cedar, and black locust was comparedwith the heartwood of the same species. Tests [9] were made on material in both the green and the air-dry condition; they included static-bending, compression-parallel-to-grain, and, with redwood, toughness tests also.

[7] See footnote 4 on p. 801.

[8] See footnote 5 on p. 801.

[9] When specimens 2 by 2 inches in cross section were used, the testing procedure followed A. S. T. M. Standard Methods of Testing Small Clear Specimens of Timber (A. S. T. M. Standards, 1927, Pt. II, Nonmetallic Materials, pp. 581–622). Static-bending specimens three-fourths by three-fourths inch in cross section were tested under center loading over a 10-inch span with a testing speed of 0.0304 inch per minute; static-bending specimens five-eighths by five-eighths inch under center loading over an 8-inch span with a testing speed of 0.0288 inch per minute; static-bending specimens one-fourth by one-fourth inch under center loading over a 3½-inch span with a testing speed of 0.0092 inch per minute; compression-parallel-to-grain specimens, in all cases, were four times the least dimension in length, and the testing speed was 0.003 inch per inch of length of specimen; the toughness tests were made on the laboratory toughness-testing machine.

TABLE 1.—*Comparison of heartwood and sapwood in the effect of extractives on strength*

GREEN WOOD

Species	Heartwood or sapwood	Trees	Bolt [a]	Annual growth, rings per inch	Hot-water extractives	Compression parallel to grain: Tests	Moisture content	Specific gravity: Value	Specific gravity: Ratio of heartwood to sapwood	Specific gravity: Heartwood specimens—Above sapwood	Specific gravity: Heartwood specimens—Below sapwood	Maximum crushing strength: Value	Ratio of heartwood to sapwood: Actual	Ratio of heartwood to sapwood: Calculated [b]	Heartwood specimens: Above sapwood	Heartwood specimens: Below sapwood
		Number			*Per cent*	*Number*	*Per cent*		*Per cent*	*Number*	*Number*	*Lbs. per sq. in.*	*Per cent*	*Per cent*	*Number*	*Number*
Virgin redwood	H [d]	3	a	18	(c)	58	182.7	0.374				4,050				
Do	H	7	e, f	24		211	117.8	.364				4,210				
Do	H	6	Top	25		137	54.0	.336				3,640				
Total		16				406										
Average [f]				23			106.0	.355	113			3,970	136	117		
Virgin redwood	S [d]	3	a	31	(c)	9	145.1	.312				2,780				
Do	S	7	e, f	32		20	158.1	.325				3,090				
Do	S	6	Top	34		20	133.5	.300				2,760				
Total		16				49										
Average [f]				33			146.4	.313				2,910				

AIR-DRY WOOD

Virgin Redwood	H [d]	3	a	18	(c)	64	11.6	0.405				6,060				
Do	H	7	e, f	24		206	11.3	.389				6,140				
Do	H	6	Top	25		142	11.2	.358				5,690				
Total		16				412										
Average [f]				23			11.3	.380	109			5,960	117	111		
Virgin redwood	S [d]	3	a	32	(c)	6	11.4	.355				4,970				
Do	S	7	e, f	31		23	11.0	.357				5,290				
Do	S	6	Top	34		20	11.6	.340				4,880				
Total		16				49										
Average [f]				32			11.3	.350				5,080				

Footnotes at end of table.

TABLE 1.—*Comparison of heartwood and sapwood in the effect of extractives on strength*—Continued

GREEN VIRGIN REDWOOD

Heartwood or sapwood	Static bending															
	Tests	Moisture content	Specific gravity				Modulus of rupture					Work to maximum load				
			Value	Ratio of heartwood to sapwood	Heartwood specimens—		Value	Ratio of heartwood to sapwood		Heartwood specimens—		Value	Ratio of heartwood to sapwood		Heartwood specimens—	
					Above sapwood	Below sapwood		Actual	Calculated [b]	Above sapwood	Below sapwood		Actual	Calculated [b]	Above sapwood	Below sapwood
	Number	*Per cent*		*Per cent*	*Number*	*Number*	*Lbs. per sq. in.*	*Per cent*	*Per cent*	*Number*	*Number*	*In.-lbs. per cu. in.*	*Per cent*	*Per cent*	*Number*	*Number*
Heartwood [d]	30	178.2	0.360				6,940					7.34				
Do	98	121.9	.376				7,480					7.50				
Do	64	57.0	.354				6,570					5.74				
Total	192															
Average [f]		108.1	.365	111			7,040	119	117			6.81	105	123		
Sapwood [d]	3	167.3	.337				5,900					7.83				
Do	10	153.8	.334				6,100					6.15				
Do	8	95.5	.316				5,650					6.21				
Total	21															
Average [f]		134.5	.328				5,890					6.49				

AIR-DRY VIRGIN REDWOOD

Heartwood [d]	27	11.7	0.398				8,900					4.89				
Do	94	11.4	.394				9,820					6.15				
Do	54	11.6	.360				8,710					5.21				
Total	175															
Average [f]		11.5	.382	109			9,230	105	114			5.56	79	119		
Sapwood [d]	4	11.6	.350				8,370					6.45				
Do	10	11.2	.368				9,550					7.62				
Do	11	12.5	.334				8,260					6.78				
Total	25															
Average [f]		11.8	.352				8,840					7.09				

Heartwood or sapwood	Moisture content	Specific gravity: Value	Specific gravity: Ratio of hardwood to sapwood	Radial toughness: Tests	Radial toughness: Value	Radial toughness: Ratio of heartwood to sapwood: Actual	Radial toughness: Ratio of heartwood to sapwood: Calculated [b]	Tangential toughness: Tests	Tangential toughness: Value	Tangential toughness: Ratio of heartwood to sapwood: Actual	Tangential toughness: Ratio of heartwood to sapwood: Calculated [b]
				GREEN VIRGIN REDWOOD							
	Toughness [c]										
	Per cent		*Per cent*	*Number*	*In.-lbs. per specimen*	*Per cent*	*Per cent*	*Number*	*In.-lbs. per specimen*	*Per cent*	*Per cent*
Heartwood [d]	180.7	0.396		20	67.9			21	99.3		
Do	115.3	.389		57	55.6			58	92.3		
Do	51.3	.352		34	43.3			33	60.2		
Total				111				112			
Average [f]	103.6	.376	110		53.3	83	121		81.6	78	121
Sapwood [d]	185.8	.338		3	68.4			1	92.9		
Do	135.4	.336		8	71.6			3	87.3		
Do	120.3	.350		5	52.8			4	131.4		
Total				16				8			
Average [f]	139.2	.341			64.0				104.9		
				AIR-DRY VIRGIN REDWOOD							
Heartwood [d]	10.5	0.400		24	46.5			24	74.1		
Do	11.0	.387		66	47.3			60	71.3		
Do	10.9	.360		40	34.0			33	49.5		
Total				130				117			
Average [f]	10.9	.379	107		42.2	71	114		63.6	75	114
Sapwood [d]	10.1	.344		3	64.6			1	61.8		
Do	11.0	.360		3	68.6			6	103.2		
Do	11.8	.355		1	46.6			8	73.9		
Total				7				15			
Average [f]	11.1	.355			59.6				84.4		

Footnotes at end of table.

TABLE 1.—*Comparison of heartwood and sapwood in the effect of extractives on strength*—Continued

GREEN WOOD

Species	Heartwood or sapwood	Trees	Bolt[a]	Annual growth rings per inch	Hot-water extractives	Compression parallel to grain: Tests	Moisture content	Specific gravity: Value	Ratio of heartwood to sapwood	Heartwood specimens—Above sapwood	Heartwood specimens—Below sapwood	Maximum crushing strength: Value	Ratio of heartwood to sapwood: Actual	Ratio of heartwood to sapwood: Calculated[b]	Heartwood specimens—Above sapwood	Heartwood specimens—Below sapwood
		Number		*Per inch*	*Per cent*	*Number*	*Per cent*		*Per cent*	*Number*	*Number*	*Lbs. per sq. in.*	*Per cent*	*Per cent*	*Number*	*Number*
Western red cedar	H[d]	1	d	22	13.05	12	39.4	0.310		12	0	2,740			12	0
Do	H	1	d	15	13.00	9	40.2	.322		9	0	3,030			9	0
Do	H	1	d	15	8.52	13	37.8	.326		13	0	2,880			13	0
Total		3				34				34	0				34	0
Average[f]				17	11.52		39.1	.319	113			2,880	126	117		
Western red cedar	S[d]	1	d	21	2.38	12	76.6	.269				2,130				
Do	S	1	d	20	2.40	9	36.9	.278				2,420				
Do	S	1	d	20	2.11	13	171.0	.303				2,310				
Total		3				34										
Average[f]				20	2.30		94.8	.283				2,290				

AIR-DRY WOOD

Species	Heartwood or sapwood	Trees	Bolt[a]	Annual growth rings per inch	Hot-water extractives	Compression parallel to grain: Tests	Moisture content	Specific gravity: Value	Ratio of heartwood to sapwood	Heartwood specimens—Above sapwood	Heartwood specimens—Below sapwood	Maximum crushing strength: Value	Ratio of heartwood to sapwood: Actual	Ratio of heartwood to sapwood: Calculated[b]	Heartwood specimens—Above sapwood	Heartwood specimens—Below sapwood
Western red cedar	H[d]	1	d	21	12.52	12	10	0.333		12	0	5,650			12	0
Do	H	1	d	15	12.48	7	10	.340		7	0	5,960			7	0
Do	H	1	d	15	8.60	12	10	.342		12	0	5,880			10	2
Total		3				31				31	0				29	2
Average[f]				17	11.20		10	.338	111			5,830	118	114		
Western red cedar	S[d]	1	d	21	2.60	12	10	.288				4,320				
Do	S	1	d	19	2.43	7	10	.304				4,940				
Do	S	1	d	19	1.98	12	10	.324				5,560				
Total		3				31										
Average[f]				20	2.34		10	.305				4,940				

Average [f]				20	2.34		10	.305				4,940							

GREEN WOOD

Black locust	H [d]	1	a	6½	9.36	6	27.6	0.659		6	0	6,190			6	0
Do	H	1	a	7½	9.84	6	38.0	.646		6	0	5,820			6	0
Total		2				12				12	0				12	0
Average [f]				7	9.60		32.8	.653	110			6,000	148	113		
Black locust	S [d]	1	a	10	6.44	6	32.7	.605				4,120				
Do	S	1	a	11	6.15	6	37.3	.580				3,990				
Total		2				12										
Average [f]				10½	6.30		35.0	.592				4,050				

AIR-DRY WOOD

Black locust	H [d]	1	a	7½	9.98	6	8	0.703		5	1	12,240			6	0
Do	H	1	a	7	9.79	6	8	.652		6	0	11,500			6	0
Total		2				12				11	1				12	0
Average [f]				7	9.89		8	.678	110			11,870	140	113		
Black locust	S [d]	1	a	13	6.30	6	8	.620				8,720				
Do	S	1	a	12	5.95	6	8	.609				8,230				
Total		2				12										
Average [f]				12½	6.13		8	.615				8,480				

Footnotes at end of table.

TABLE 1.—*Comparison of heartwood and sapwood in the effect of extractives on strength*—Continued

GREEN WESTERN RED CEDAR

Heartwood or sapwood	Static bending															
	Tests	Moisture content	Specific gravity				Modulus of rupture					Work to maximum load				
			Value	Ratio of heartwood to sapwood	Heartwood specimens—		Value	Ratio of heartwood to sapwood		Heartwood specimens—		Value	Ratio of heartwood to sapwood		Heartwood specimens—	
					Above sapwood	Below sapwood		Actual	Calculated [b]	Above sapwood	Below sapwood		Actual	Calculated [b]	Above sapwood	Below sapwood
	Number	*Per cent*		*Per cent*	*Number*	*Number*	*Lbs. per sq. in.*	*Per cent*	*Per cent*	*Number*	*Number*	*In.-lbs. per cu. in.*	*Per cent*	*Per cent*	*Number*	*Number*
Heartwood [d]	12	36.6	0.313		11	1	5,460			12	0	6.28			6	6
Do	9	38.2	.321		9	0	5,770			9	0	6.40			7	2
Do	13	31.3	.325		13	0	6.410			13	0	8.72			6	5
Total	34				33	1				34	0				19	13
Average [f]		35.4	.320	113			5,880	124	120			7.13	111	128		
Sapwood [d]	12	75.2	.263				4,320					5.97				
Do	9	36.0	.283				4,760					5.42				
Do	13	182.0	.304				5,160					7.83				
Total	34															
Average [f]		97.7	.283				4,750					6.41				
AIR-DRY WESTERN RED CEDAR																
Heartwood [d]	12	10	0.333		12	0	9,430			12	0	8.88			7	5
Do	8	10	.341		8	0	10,250			8	0	9.59			3	5
Do	12	10	.343		11	1	10,280			11	1	11.79			6	6
Total	32				31	1				31	1				16	16
Average [f]		10	.339	112			9,990	119	118			10.10	105	125		
Sapwood [d]	12	10	.287				7,650					8.07				
Do	8	10	.303				8,410					8.98				
Do	12	10	.323				9,200					11.70				
Total	32															
Average [f]		10	.304				8,420					9.58				

Average [f]		10	.304				8,420					9.58				

GREEN BLACK LOCUST

Heartwood [d]	6	45.9	0.680		6	0	14,460			6	0	32.8			4	2
Do	6	58.1	.637		6	0	14,030			6	0	30.7			5	1
Total	12				12	0				12	0				9	3
Average [f]		52.0	.658	113			14,240	133	120			31.8	116	128		
Sapwood [d]	6	44.4	.596				10,940					28.4				
Do	6	49.8	.571				10,450					26.3				
Total	12															
Average [f]		47.1	.584				10,700					27.4				

AIR-DRY BLACK LOCUST

Heartwood [d]	6	8	0.728		6	0	27,100			6	0	41.1			4	2
Do	6	8	.700		6	0	26,100			6	0	36.3			4	2
Total	12				12	0				12	0				8	4
Average [f]		8	.714	109			26,600	134	114			38.7	116	119		
Sapwood [d]	6	8	.664				20,700					36.3				
Do	6	8	.649				19,050					30.7				
Total	12															
Average [f]		8	.656				19,880					33.5				

[a] The letter "a" designates the first log section or bolt, 4 feet in length, taken above the stump; "b" the second 4-foot bolt; and so forth.

[b] Calculated heartwood value = $\left\{\frac{\text{Heartwood sp. gr.}}{\text{Sapwood sp. gr.}}\right\}^{x}$ (sapwood strength value). The values of x are: For maximum crushing strength, 1.25; modulus of rupture, 1.50; work to maximum load, 2.00; and toughness, 2.00.

[c] Specimens ¾ by ¾ by 10 inches were tested over an 8-inch span with center loading.

[d] The first entry in each comparable group reports specimens from the same trees, and the succeeding entries in the same groups correspond similarly.

[e] A large number of determinations made in an earlier study of similar material indicate that the hot-water extractives of virgin redwood heartwood average about 10 to 15 per cent.

[f] The individual values were weighted in accordance with the number of trees represented.

Redwood

The redwood static-bending and compression-parallel-to-grain specimens were 2 by 2 inches in cross section. Adjoining specimens, cut from a strip extending across the full section as indicated in Figure 1, A, were used. The toughness specimens, which were ⅝ by ⅝ by 10 inches, were cut from the uninjured end of the static-bending specimens after the first test. The results of all these tests are given in Table 1.

The averages of the results of tests of both heartwood and sapwood specimens from the butt (bolt a),[10] second log (bolts e–f), and top of merchantable length are given. The results are also expressed as ratios of heartwood to sapwood. In addition, calculated ratios of heartwood to sapwood are presented; these are the ratios to be expected if extractives increase the strength of wood in the same ratio as an equal weight of wood substance. The exact method of calculation is given in footnote *b* of Table 1.

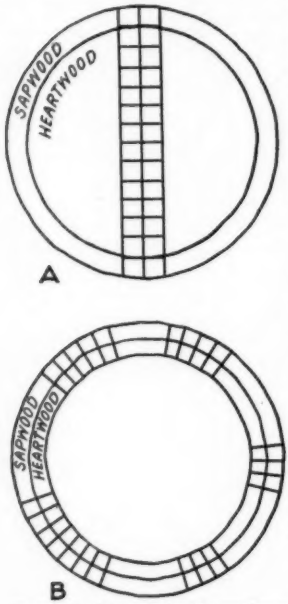

FIGURE 1.—Diagram for the cutting of samples: A, virgin redwood; B, western red cedar and black locust

The specific gravity of the heartwood of redwood, as shown by tests on green material, is approximately 10 per cent higher than that of the sapwood, a fact that indicates higher strength values for heartwood than for sapwood. Actual ratios compared with calculated ones showed that the maximum crushing of the strength of the green heartwood was higher than that of the sapwood by an amount about twice as great as that which would be expected from a like increase of wood substance. Modulus of rupture showed about the difference indicated by the calculated ratios, while in work to maximum load the increase was considerably less, the heartwood being only slightly higher than the sapwood in this property. The toughness tests showed the heartwood to be actually lower than the sapwood, although the difference in weights indicates considerably higher values. The increase in the weight of redwood through the infiltration of extractives, and perhaps other substances, apparently does not affect all properties of green wood in the same way; the change increases some properties, has little effect on others, and actually reduces still others. When a property, work to maximum load for instance, is in a general way inversely proportional to another property, compressive strength in this instance, an increase in the compressive strength will usually decrease the work to maximum load.

When redwood was tested in the air-dry condition, the difference in strength between heartwood and sapwood was not the same as for a

[10] The letter "a" designates the first log section or bolt, 4 feet in length, taken above the stump, "b" the second 4-foot bolt, and so forth.

green condition. The tests showed that the compressive strength of the heartwood as compared with that of the sapwood was higher than the value that would result from a like difference in weight of wood substance, but not to the degree of the redwood tested in a green condition; similarly the modulus of rupture of air-dry heartwood was proportionally somewhat lower, and the work to maximum load much lower, in fact even lower than the lighter weight sapwood. The ratios from the toughness tests were similar to those from work-to-maximum-load values; both properties are measures of shock resistance.

The tests of both green and air-dry redwood indicate that redwood heartwood as compared to sapwood on a weight-strength basis is considerably higher in maximum crushing strength in compression parallel to grain, slightly higher in modulus of rupture, and in most instances lower in shock resistance. Since, as far as is known, there are no structural differences between heartwood and sapwood that could account for the differences in strength, and since, as is shown later, the infiltration and removal of extractives affect the strength, probably these differences in strength are primarily due to extractives.

Western Red Cedar

Sapwood and adjoining heartwood specimens were so selected as to be representative of the entire outer cross section of the tree, as indicated in Figure 1, B. Only trees with sapwood and adjoining heartwood of approximately the same rate of growth were used. Compression-parallel-to-grain and static-bending tests were made. The sapwood in western red cedar is relatively thin and so, to obtain specimens that were all sapwood, relatively small pieces three-fourths by three-fourths inch in cross section were tested.

The results of tests of green western red cedar as shown in Table 1 are similar to those of green redwood; the maximum crushing strength of the heartwood exceeds that of the sapwood by an amount greater than that which the calculated ratios indicate and the actual ratios of moduli of rupture are about equal to the calculated ratios, while the work to maximum load of the heartwood does not exceed that of the sapwood to the extent calculated from the weight-strength ratios.

Extractives apparently affect the strength of air-dry western red cedar in about the same manner as when it is green, while with redwood the effect was somewhat less.

Black Locust

The test specimens of black locust were selected in the same manner as those of western red cedar. (Fig. 1, B.) In selecting trees for test purposes, uniform rate of growth of sapwood and adjoining heartwood was the principal factor considered; even so, a considerable range in rate of growth existed. The sapwood in black locust is extremely thin and, to obtain specimens entirely of sapwood, pieces only one-fourth by one-fourth inch in cross section were used. Compression-parallel-to-grain and static-bending tests with the wood in both a green and an air-dry condition were also made on this species.

The increase in the strength of black locust heartwood as compared with the sapwood was more than for either redwood or western red

cedar. (Table 1.) The maximum crushing strength in compression-parallel-to-grain and also the modulus of rupture of the heartwood as compared with those of the sapwood are considerably higher than the values that would result from like differences in the amount of wood substance. For green wood, the increase in work to maximum load can be accounted for without recourse to extractives, but for air-dry wood the extractives must be included as a cause of this increase. Although the difference between heartwood and sapwood in work to maximum load is not so large as the difference in weight would indicate, still it is much more in line with the weight-strength ratios than for redwood and western red cedar.

Throughout this article, as already suggested, the evaluations of test results are made as if the additional weight of extractives in a piece of wood were an additional weight of wood substance. Further, even though the extractives may have actually increased the strength, if the increase was less than that which an equal weight of wood substance would have given, then the percentages in the tables indicate in general a failure to reach full expected increase rather than a minor increase. Black locust, however, differs from redwood and western red cedar enough to make desirable an additional analysis of part of the results for it. Unlike the other species, the sapwood of black locust as well as the heartwood is relatively high in extractives, and the difference in weight between the heartwood and the sapwood tested is therefore due primarily to wood substance rather than to extractives. In the calculations made during the analysis, but not reported here, the specific-gravity values for this species were corrected to those for wood substance alone; the results showed that the increase in wood substance itself is sufficient to account for the increase in work to maximum load of green black locust heartwood as compared with the sapwood. On the other hand, the extractives must be considered a contributing cause for such increase in air-dry black locust.

EFFECT OF REMOVING EXTRACTIVES

If the addition of extractives in the natural physiological change of sapwood into heartwood increases some of the strength properties of certain woods, the removal of these extractives should be expected to decrease these strength properties. In order to determine the effect on the strength of removing extractives, three series of tests comparing extracted to unextracted wood were made, as follows:

Series 1.—Compression-parallel-to-grain tests of specimens cut from redwood blocks 6 inches in length.

Series 2.—Compression-parallel-to-grain and static-bending tests of specimens cut from redwood blocks 24 inches in length.

Series 3.—Compression-parallel-to-grain and static-bending tests of specimens cut from white spruce blocks 11 inches or 18 inches in length.

The tests on white spruce (series 3), which is low in extractives, were included to determine whether any change in mechanical properties was due to method rather than to the removal of the extractives themselves.

TABLE 2.—*Average strength values of wood from which extractives were partly removed, by forcing cold water along the grain, compared with the values of unextracted wood*

GREEN WOOD

Species	Series No.	Kind of specimen	Tree No.	Length of piece	Cross section of specimen	Time of extraction	Hot-water extractives	Compression parallel to grain												
								Tests	Moisture content	Specific gravity				Maximum crushing strength					
										Value	Ratio of value to base [a]	Specimens—		Value	Ratio of value to base [a]	Specimens—		Specific gravity ratio to 1.25 power	
												Above base [a]	Below base [a]			Above base [a]	Below base [a]	Value	Base multiplied by value
				Ins.	*Inch*	*Days*	*Per cent*	*No.*	*Per cent*		*Per cent*	*No.*	*No.*	*Lbs. per sq. in.*	*Per cent*	*No.*	*No.*	*Per cent*	*Lbs. per sq. in.*
Virgin redwood	1	Extracted wood	65	6	½ x ½	69	6.11	8	102.2	0.388	91	0	8	3,700	82	0	8		
Do	1	do	66	6	½ x ½	78	4.08	9	105.9	.383	94	1	8	3,420	83	0	9		
Total								17				1	16			0	17		
Average						74	5.10		104.0	.386	92			3,560	83			91	3,910
Virgin redwood	1	Adjacent control [b]	65	6	½ x ½		13.52	16	50.1	.428				4,480					
Do	1	do	66	6	½ x ½		8.95	18	48.2	.406				4,120					
Total								34											
Average							11.28		49.2	.417				4,300					

AIR-DRY WOOD

Virgin redwood	1	Extracted wood	65	6	½ x ½	69	6.11	8	9.4	0.409	92	0	8	6,880	92	0	8		
Do	1	do	66	6	½ x ½	78	4.08	9	10.1	.399	96	1	8	6,250	80	1	8		
Total								17				1	16			1	16		
Average						74	5.10		9.8	.404	94			6,560	86			93	7,120
Virgin redwood	1	Adjacent control [b]	65	6	½ x ½		13.62	16	9.4	.442				7,500					
Do	1	do	66	6	½ x ½		8.95	18	10.1	.416				7,810					
Total								34											
Average							11.28		9.8	.429				7,660					

Footnotes at end of table.

TABLE 2.—*Average strength values of wood from which extractives were partly removed, by forcing cold water along the grain, compared with the values of unextracted wood*—Continued

GREEN WOOD

Species	Series No.	Kind of specimen	Tree No.	Length of piece	Cross section of specimen	Time of extraction	Hot-water extractives	Compression parallel to grain											
								Tests	Moisture content	Specific gravity				Maximum crushing strength					
										Value	Ratio of value to base [a]	Specimens—		Value	Ratio of value to base [a]	Specimens—		Specific gravity ratio to 1.25 power	
												Above base [a]	Below base [a]			Above base [a]	Below base [a]	Value	Base multiplied by value
				Ins.	*Inch*	*Days*	*Per cent*	*No.*	*Per cent*		*Per cent*	*No.*	*No.*	*Lbs. per sq. in.*	*Per cent*	*No.*	*No.*	*Per cent*	*Lbs. per sq. in.*
Virgin redwood	2	Extracted wood	65	24	¾ x ¾	124	5.89	10	70.0	0.410	95	0	8	4,310	88	1	8		
Do	2	do	66	24	¾ x ¾	120	4.08	14	116.6	.368	97	2	12	3,360	86	0	14		
Total								24				2	20			1	22		
Average						122	4.98		93.3	.389	96			3,840	87			95	4,180
Virgin redwood	2	Adjacent control [b]	65	24	¾ x ¾		10.68	9	60.8	.433				4,890					
Do	2	do	66	24	¾ x ¾		8.37	14	88.9	.378				3,910					
Total								23											
Average							9.53		74.8	.406				4,400					
Virgin redwood	2	Separate control [c]	65		¾ x ¾		13.30	5	65.3	.442	102	4	1	4,960	101	2	3		
Do	2	do	66		¾ x ¾		10.32	7	81.2	.397	105	7	0	4,220	108	7	0		
Total								12				11	1			9	3		
Average							11.81		73.2	.420	104			4,590	104			105	4,620

AIR-DRY WOOD

Virgin redwood	2	Extracted wood	65	24	¾ x ¾	124	5.89	10	13.0	0.422	97	4	6	6,600	99	4	6		
Do	2	do	66	24	¾ x ¾	120	4.08	14	11.3	.390	97	2	12	5,790	96	7	7		
Total								24				6	18			11	13		
Average						122	4.98		12.2	.406	97			6,200	98			96	6,100
Virgin redwood	2	Adjacent control [b]	65	24	¾ x ¾		10.68	10	13.0	.433				6,680					
Do	2	do	66	24	¾ x ¾		8.37	14	11.3	.402				6,000					
Total								24											
Average							9.52		12.2	.418				6,340					
Virgin redwood	2	Separate control [c]	65		¾ x ¾		13.30	5	13.0	.458	106	5	0	7,250	109	5	0		
Do	2	do	66		¾ x ¾		10.32	7	11.3	.406	101	4	3	5,940	99	3	4		
Total								12				9	3			8	4		
Average							11.81		12.2	.432	104			6,600	104			105	6,660

Footnotes at end of table.

TABLE 2.—*Average strength values of wood from which extractives were partly removed, by forcing cold water along the grain, compared with the values of unextracted wood*—Continued

GREEN VIRGIN REDWOOD

Kind of specimen	Series No.	Static bending																	
		Tests	Moisture content	Specific gravity				Modulus of rupture						Work to maximum load					
				Value	Ratio of value to base [a]	Specimens—		Value	Ratio of value to base [a]	Specimens—		Specific gravity ratio to 1.50 power		Value	Ratio of value to base [a]	Specimens—		Specific gravity ratio to 2.00 power	
						Above base [a]	Below base [a]			Above base [a]	Below base [a]	Value	Base multiplied by value			Above base [a]	Below base [a]	Value	Base multiplied by value
		No.	*Per cent*		*Per cent*	*No.*	*No.*	*Lbs. per sq. in.*	*Per cent*	*No.*	*No.*	*Per cent*	*Lbs. per sq. in.*	*In.-lbs. per cu. in.*	*Per cent*	*No.*	*No.*	*Per cent*	*In.-lbs. per sq. in.*
Extracted wood	2	5	164.0	0.404	91	0	5	8,010	87	0	5			10.90	89	1	4		
Do	2	7	116.6	.360	92	0	7	6,770	89	0	7			8.68	100	2	5		
Total		12				0	12			0	12					3	9		
Average			140.3	.382	92			7,390	88			88	7,400	9.79	94			84	8.80
Adjacent control [b]	2	5	82.0	.443				9,230						12.22					
Do	2	7	88.8	.390				7,600						8.73					
Total		12																	
Average			85.4	.416				8,420						10.48					
Separate control [c]	2	5	78.6	.441	100	3	2	9,190	100	3	2			12.46	102	2	3		
Do	2	7	81.2	.404	104	6	1	7,970	105	6	1			8.43	97	3	4		
Total		12				9	3			9	3					5	7		
Average			79.9	.423	102			8,580	102			103	8,670	10.44	100			104	10.90

AIR-DRY VIRGIN REDWOOD

Extracted wood	2	5	13.0	0.425	96	1	4	11,700	100	3	2			10.85	110	4	1		
Do	2	7	11.3	.387	98	1	6	9,190	93	3	4			7.98	97	3	4		
Total		12				2	10			6	6	96	10,350	9.42	104	7	5	94	8.51
Average			12.2	.406	97			10,440	96										
Adjacent control [b]	2	5	13.0	.442				11,700						9.90					
Do	2	7	11.3	.394				9,880						8.20					
Total		12																	
Average			12.2	.418				10,790						9.05					
Separate control [c]	2	5	13.0	.460	104	5	0	11,800	101	2	3			9.18	93	3	2		
Do	2	7	11.3	.407	103	4	3	10,620	108	5	2			8.59	105	4	3		
Total		12				9	3			7	5	106	11,430	8.88	90	7	5	108	9.77
Average			12.2	.434	104			11,210	104										

Footnotes at end of table.

TABLE 2.—*Average strength values of wood from which extractives were partly removed, by forcing cold water along the grain, compared with the values of unextracted wood*—Continued

GREEN WOOD

Species	Series No.	Kind of specimen	Tree No.	Length of piece	Cross section of specimen	Time of extraction	Hot-water extractives	Compression parallel to grain											
								Tests	Moisture content	Specific gravity				Maximum crushing strength				Specific gravity ratio to 1.25 power	
										Value	Ratio of value to base [a]	Specimens—		Value	Ratio of value to base [a]	Specimens—			
												Above base [a]	Below base [a]			Above base [a]	Below base [a]	Value	Base multiplied by value
				Ins.	*Inch*	*Days*	*Per cent*	*No.*	*Per cent*		*Per cent*	*No.*	*No.*	*Lbs. per sq. in.*	*Per cent*	*No.*	*No.*	*Per cent*	*Lbs. per sq. in.*
White Spruce	3	Extracted wood	196	11	1/2 x 1/2	29		8	53.1	0.369	105	7	1	2,410	102	5	3		
Do	3	do	196	18	5/8 x 5/8	93	2.04	7	135.3	.341	102	5	2	2,270	99	2	5		
Total								15				12	3			7	8		
Average						61			109.2	.355	104			2,340	100			105	2,450
White spruce	3	Adjacent control [b]	196	11	1/2 x 1/2			16	51.1	.350	100			2,360					
Do	3	do	196	18	5/8 x 5/8		2.60	7	73.4	.335	96			2,300					
Total								23											
Average									62.3	.343				2,330					
White spruce	3	Separate control [c]	196		1/2 x 1/2			14	36.3	.348	100	4	10	2,320	98	6	8		
Do	3	do	196		5/8 x 5/8		2.53	7	31.6	.349	104	6	1	2,490	108	5	2		
Total								21				10	11			11	10		
Average									34.0	.348	102			2,410	103			102	2,380

AIR-DRY WOOD

White spruce	3	Extracted wood	196	11	½ x ½	29		8	11.2	0.386	100	5	3	5,830	102	7	1		
Do	3	do	196	18	⅝ x ⅝	93	2.04	7	13.0	.366	102	5	2	5,230	108	6	1		
Total								15				10	5			13	2		
Average						61			12.1	.376	101			5,530	105			101	5,340
White spruce	3	Adjacent control [b]	196	11	½ x ½			16	11.1	.384				5,710					
Do	3	do	196	18	⅝ x ⅝		2.60	7	13.0	.357				4,850					
Total								23											
Average									12.0	.370				5,280					
White spruce	3	Separate control [c]	196		½ x ½			14	11.0	.388	101	9	5	6,020	106	11	3		
Do	3	do	196		⅝ x ⅝		2.53	7	13.0	.373	104	6	1	4,620	95	3	4		
Total								21				15	6			14	7		
Average									12.0	.380	102			5,320	100			103	5,440

Footnotes at end of table.

TABLE 2.—*Average strength values of wood from which extractives were partly removed, by forcing cold water along the grain, compared with the values of unextracted wood*—Continued

GREEN WHITE SPRUCE

5/6 x 5/6 inch in cross section

Kind of specimens	Series No.	Static bending																	
		Tests	Moisture content	Specific gravity				Modulus of rupture						Work to maximum load					
				Value	Ratio of value to base [a]	Specimens—		Value	Ratio of value to base [a]	Specimens—		Specific gravity ratio to 1.50 power		Value	Ratio of value to base [a]	Specimens—		Specific gravity ratio to 2.00 power	
						Above base [a]	Below base [a]			Above base [a]	Below base [a]	Value	Base multiplied by value			Above base [a]	Below base [a]	Value	Base multiplied by value
		No.	*Per cent*		*Per cent*	*No.*	*No.*	*Lbs. per sq. in.*	*Per cent*	*No.*	*No.*	*Per cent*	*Lbs. per sq. in.*	*In.-lbs. per cu. in.*	*Per cent*	*No.*	*No.*	*Per cent*	*In.-lbs. per sq. in.*
Extracted wood	3	7	188.4	0.353	104	5	2	5,770	106	6	1	106	5,740	7.97	133	7	0	108	6.46
Adjacent control [b]	3	7	91.2	.338				5,420						5.98					
Separate control [c]	3	7	31.2	.357	106	5	2	5,890	109	5	2	109	5,900	9.79	164	6	1	112	6.70

AIR-DRY WHITE SPRUCE

5/6 x 5/6 inch in cross section

Extracted wood	3	7	13.0	0.374	103	5	2	9,400	104	3	4	104	9,450	6.16	95	3	4	106	6.85
Adjacent control [b]	3	7	13.0	.364				9,070						6.47					
Separate control [c]	3	7	13.0	.386	106	7	0	9,320	103	5	2	109	9,900	8.16	126	5	2	112	7.24

[a] The base values are the averages under "Adjacent control."
[b] Cut from the outer part of the piece through the center of which water was forced.
[c] Cut from the same annual growth rings as the extracted specimens but not adjacent to them.

The method [11] for removing extractives was merely to force cold water through the wood in the direction of the grain, and in detail was as follows:

Green redwood boards 2½ inches thick, 10 to 12 inches wide, and 6 to 24 inches long were used. A ¾-inch hole was bored near the middle of the length (fig. 2), into the side grain of the narrow face, and to within 1 inch of the opposite face. A pipe threaded at its end was then screwed in for about 1 inch, after which it was attached to a water main that was under a pressure of about 80 pounds per square inch. Since water moves along the grain much more rapidly than across the grain, the portion of the piece indicated by dotted lines in Figure 2 was the natural course for the water, and hence this portion lost a much larger percentage of extractives than the remainder. Water was allowed to seep through the 6-inch pieces for about 70 days, and the 24-inch pieces for about 120 days. The total amount of water passing through was about the same for the short as for the long pieces, during the test periods, although a slightly greater percentage of extractives was removed from the short ones.

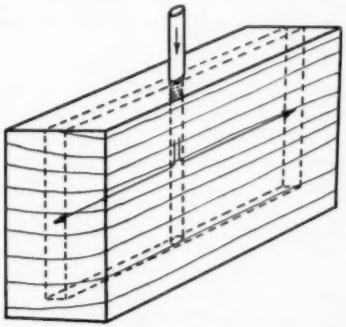

FIGURE 2.—The course of the main flow of water in test material

The specimens from the central portion of the board, from which a large part of the extractives had been removed, were compared with specimens taken from near the face of the board. Since these boards were quarter-sawed and the hole was bored into the narrow face, matched specimens came from the same annual rings. Other specimens carefully matched to the treated specimens but not part of the treated piece were also tested as controls. The specimens were from one-half to three-fourths inch square in cross section. Tests of material in both the green and the air-dry condition were made. In series 2 and 3, where both compression-parallel-to-grain and static-bending tests were made, two compression-parallel-to-grain specimens were obtained from the ends of the static-bending specimen after test.

The results of these tests are presented in Table 2.

The amount of extractives remaining in the portion of the redwood pieces leached by water was approximately 5 per cent [12] and the remainder of the board had about 10 per cent. Control pieces carefully matched to the treated piece had an extractive content of approximately 12 per cent, indicating that the outer portion of the treated board lost some extractives while the interior portion lost over half. The strength ratios given in Table 2 are based on the strength of the outer portion of the treated board, and since this material had also lost some extractives, the indicated changes in strength caused by the removal of extractives from the inner portion of the board are probably somewhat less than those that actually occurred.

[11] This method of forcing water through a board was conceived by H. D. Tiemann of the Forest Product Laboratory.

[12] The percentage of extractives is based on the weight of the wood, oven-dry for all specimens.

Results of Series 1 and 2 Tests

When the redwood specimens were tested in a green condition the loss in extractives caused a loss in maximum crushing strength approximately twice that which would normally accompany a like reduction in the amount of wood substance. The loss in modulus of rupture was about the value that would accompany a like loss in the amount of wood substance, while the work to maximum load was decreased even less than would be expected from an equal loss in weight of wood substance. These findings, which in effect are that removal of extractives affected the strength properties inversely from the infiltration of extractives, substantiate the theory that the difference in strength between heartwood and sapwood of redwood is primarily due to extractives.

With air-dry redwood both the maximum crushing strength and the modulus of rupture showed less percentage reduction from the removal of extractives than in green material. Work to maximum load showed a slight increase because of the removal of extractives. These results are in agreement with the tests of air-dry sapwood and heartwood.

The series 1 specimens had a higher proportion of extractives removed than the series 2. Comparing these two series, it may be seen that the maximum crushing strength was lowest for the pieces showing the greatest reduction in weight, indicating that the more of the extractives removed the greater the effect upon the strength.

Results of Series 3 Tests

The leaching treatment of white spruce apparently did not decrease the weight of the wood. In fact, the outer portion of the treated blocks was lower in specific gravity than the central portion, through which most of the water undoubtedly flowed. The maximum-crushing-strength and modulus-of-rupture values for both green and air-dry material from the central portion of the treated block were also higher than those for the outer portion, and compared favorably with the carefully matched control specimens that were not part of the treated block. In work to maximum load the central portion of green material was considerably higher than the outer portion, while in the air-dry wood the reverse was true. The tests on white spruce indicate little, if any, effect on the weight and the strength of this wood resulting from the process used for removing extractives.

EFFECT OF INCREASING THE CONCENTRATION OF EXTRACTIVES THROUGH DRYING

If the removal of extractives affects the strength of redwood, then an increase in concentration should also affect it. Sherrard [13] has shown that when redwood is dried there is a transfer of extractives from the center outward that results in a higher concentration near the surface. Tests were made to compare the effect of this increase in concentration on the strength. Specimens from the outermost part of the block were compared with specimens from the same block and the same annual rings but slightly nearer the center of the piece. The high extractive content decreases very rapidly from the outer

[13] Unpublished data.

surface inward; the first quarter inch from the surface averaged over 12 per cent extractives, while the second quarter inch averaged only 5 per cent. Therefore, to get a large difference in extractives in closely matched pieces small specimens were necessary, and pieces one-fourth by one-fourth inch in cross section were used. Compression-parallel-to-grain and static-bending tests were made, the results of which are shown in Table 3. Specimens from two trees were tested and similar results were obtained for both sets of specimens.

The difference in specific gravity of the first quarter inch of material from the surface compared with the second quarter inch was approximately 6 per cent; this difference was undoubtedly due to the transfer of extractives during drying. In compression-parallel-to-grain tests the outer layer was about 7 per cent higher in strength than the inner one and the modulus of rupture was about 4 per cent higher, while work to maximum load showed little change. Although the differences are not large, the fact that there is a change and that individual specimens were quite consistent in showing a change is further evidence that extractives do affect the strength properties.

EFFECT OF ADDING EXTRACTIVES

Another method used for determining the effect of extractives on the strength was to soak small, green, sapwood specimens of redwood in a solution of redwood extractives. The solution, which was expressed from green redwood by the cooperating company [14] that supplied it, had an extractive concentration of 3.83 per cent. Only short specimens 2 inches in length were treated, since the greatest increase in extractive content through soaking naturally occurs at the ends. These short pieces permitted only compression-parallel-to-grain tests.

In addition to the sapwood pieces soaked in a redwood solution, pieces carefully matched for control were soaked in water under conditions otherwise identical, and were then compared with matched untreated controls. The results of the tests are shown in Table 4.

Soaking sapwood specimens of redwood in water had little effect on the specific gravity of the oven-dry wood or on the maximum crushing strength. When soaked in redwood extractives, the specific gravity oven-dry was increased about 10 per cent. The maximum crushing strength was slightly increased, but the change was small in comparison with the change in weight caused by the addition of extractives. These comparisons held for material tested immediately after soaking as well as for that subsequently air-dried.

The relatively small increase in crushing strength as compared with the increase in weight caused by the infiltration of extractives is probably due to the high concentration of extractives near the ends of the specimens and the lower concentration near the center, where practically all of the failures occurred. Although no marked change in strength was shown as a consequence of soaking the specimens in extractives, the fact that some increase resulted and that this increase was fairly consistent is of interest as further evidence that extractives do affect the strength.

[14] The redwood for this investigation was supplied by the California Redwood Association and the solution of extractives by the Little River Redwood Co. of Crannell, Calif.

TABLE 3.—*The strength values of the outer portion of virgin redwood timber, the extractive content of which has been increased through kiln drying, compared with those of the interior*

OUTER PART OF KILN-DRIED PIECE

Tree No.	Kind of specimen [a]	Tests	Cold-water extractives	Compression parallel to grain									Static bending										
				Moisture content	Specific gravity				Maximum crushing strength				Moisture content	Specific gravity				Modulus of rupture				Work to maximum load			
					Value	Ratio of *k* to *m*	*k* specimens—		As tested	Adjusted to 10 per cent moisture content				Value	Ratio of *k* to *m*	*k* specimens—		As tested	Adjusted to 10 per cent moisture content				Ratio of *k* to *m*	*k* specimens—	
							Above *m*	Below *m*		Value	Ratio of *k* to *m*	*k* specimens—							Value	Ratio of *k* to *m*	*k* specimens—					
												Above *m*	Below *m*								Above *m*	Below *m*				Above *m*	Below *m*
		No.	*Per cent*	*Per cent*		*Per cent*	*No.*	*No.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Per cent*	*No.*	*No.*	*Per cent*		*Per cent*	*No.*	*No.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Per cent*	*No.*	*No.*	*In.-lbs. per cu. in.*	*Per cent*	*No.*	*No.*
.....	*k*	8	13.67	9.5	0.437	.....	8	0	6,470	6,360	.....	7	1	10.6	0.446	.....	8	0	11,800	12,000	.....	6	2	10.00	.....	5	3
66.....	*k*	10	10.93	7.2	.454	.....	5	5	7,600	7,000	.....	7	3	7.6	.481	.....	7	3	13,140	12,450	.....	8	2	12.88	.....	5	4
Total.....	.....	18	.....	.....	.....	.....	13	5	.....	.....	.....	14	4	.....	.....	.....	15	3	.....	.....	.....	14	4	.....	.....	10	7
Average..	.....	.....	12.30	8.3	.446	105	.....	.....	7,040	6,680	107	.....	.....	9.1	.464	107	.....	.....	12,470	12,230	104	.....	.....	11.44	102	.....	.....

INNER PART OF KILN-DRIED PIECE

.....	*m*	8	6.83	10.7	0.395	.....	.....	.....	5,700	5,820	.....	.....	.....	11.7	0.395	.....	.....	.....	11,100	11,550	.....	.....	.....	9.89	.....	.....	.....
66.....	*m*	10	5.02	7.8	.458	.....	.....	.....	7,170	6,720	.....	.....	.....	8.1	.475	.....	.....	.....	12,450	11,900	.....	.....	.....	12.68	.....	.....	.....
Total.....	.....	18	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Average..	.....	.....	5.92	9.2	.426	.....	.....	.....	6,440	6,270	.....	.....	.....	9.9	.435	.....	.....	.....	11,780	11,730	.....	.....	.....	11.28	.....	.....	.....

[a] Specimens from the surface of kiln-dried timber, which are high in extractives, are designated *k*. Specimens adjacent to the outside pieces, which are considerably lower in extractives, are designated *m*

TABLE 4.—*The maximum crushing strength of virgin redwood sapwood, impregnated with redwood extractives, compared with that of unimpregnated wood*

GREEN WOOD

Condition of specimen	Matching [a] of specimens	Tests	Moisture content	Specific gravity				Maximum crushing strength			
				Value	Ratio of treated to control specimen	Impregnated specimens—		Value	Ratio of treated to control specimen	Impregnated specimens—	
						Above controls	Below controls			Above controls	Below controls
		Number	*Per cent*		*Per cent*	*Number*	*Number*	*Lbs. per sq. in.*	*Per cent*	*Number*	*Number*
Soaked in water	A	6	38.6	0.322	101	3	3	2,700	102	3	3
Green	do	6	35.8	.320				2,650			
Soaked in extractives	B	6	61.0	.356	111	6	0	2,770	[b] 102	4	2
Green	do	6	35.7	.322				2,720			
AIR-DRY WOOD											
Soaked in water and air dried	C	6	9.5	0.342				4,790			
Adjusted for moisture	do	6	9.6	.342	101	2	4	4,770	95	2	4
Air dried	do	6	9.6	.340				5,020			
Soaked in extractives and air dried	D	6	9.2	.370				5,270			
Adjusted for moisture	do	6	9.8	.370	109	6	0	5,190	[b] 102	3	3
Air dried	do	6	9.8	.340				5,090			

[a] All specimens were intermatched, but those carrying the same letter were matched somewhat more closely than the others.

[b] Both the relatively high increase in weight and the small increase in strength resulting from the injection of extractives may be caused by the concentration of the extractives near the ends of the pieces. The failure of extractive-impregnated specimens occurred consistently near the middle of the length.

CONCLUSIONS

The several methods of investigation employed show that extractives affect the strength properties of the species of wood examined. The extent of this effect depends upon the amount of extractives, the species of wood, the moisture condition of the piece, and the mechanical property under consideration. Of the properties considered, the compressive strength parallel to the grain appears to show the greatest increase because of the normal infiltration of extractives in the change of sapwood into heartwood, the modulus of rupture is next, and shock resistance is least. In fact, under some conditions the shock resistance appears to be actually lowered by extractives. That extractives may affect different species differently is indicated by the fact that they change the strength of western red cedar less than the strength of black locust, although black locust has a smaller percentage of extractives. When the mechanical properties of wood do not vary regularly with the specific gravity, the presence of extractives or irregularity in their content may be at least a contributing factor.

SUMMARY

Extractives, which occur in the wood of many species, are especially abundant in redwood, western red cedar, black locust, and a few others. The three species mentioned are also relatively high in certain strength properties, for the amount of wood substance they contain, and no study of this peculiarity has heretofore been made at the Forest Products Laboratory. The tests reported here were made for the purpose of determining whether a relation exists between the extractive content of wood and its strength.

Four distinctly different test methods were used, and all of them indicated strongly that extractives do affect the strength of wood. Of the properties studied, compressive strength parallel to the grain appears to be increased most by the presence of extractives, bending strength as measured by modulus of rupture next, and shock resistance least.

STUDIES ON SCLEROTIA AND MYCELIAL STRANDS OF THE COTTON ROOT-ROT FUNGUS[1]

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INTRODUCTION

The discovery of a true sclerotial stage in the life history of the cotton root-rot fungus, *Phymatotrichum omnivorum* (Shear) Duggar, was reported by King and Loomis[2] from laboratory observations made at Sacaton, Ariz., in September, 1928. The relationship of these hold-over bodies to the disease was further confirmed by Neal,[3] who first reported the discovery of sclerotia under natural conditions in the soil, at Greenville and San Antonio, Tex., in 1929; and by Taubenhaus and Ezekiel,[4] who have also reported finding sclerotia under field conditions in Texas. During the season of 1930 the writers found them in great numbers in several areas in Arizona, but they occurred only in limited parts of the infected spots.

In order to determine the relationship of these structures to the dissemination of the disease and to its maintenance for long periods in the soil, an investigation of their properties was undertaken at the United States field station at Sacaton. Inoculation experiments were conducted and various tests were made to ascertain the length of time the sclerotia remained viable under different conditions and the strength of disinfecting solutions required to kill them.

To permit of uniform comparison in all the tests of sclerotia, only well-developed simple individuals were used. On account of the extreme variability in size and form of the compound sclerotia and the short life and lack of vigor of the smallest simple individuals, these types were not selected.

INOCULATION STUDIES

Since it was found that the sclerotia germinated readily, producing the characteristic root-rot mycelium, it seemed reasonable to suppose that they might be able to infect healthy plants when brought in contact with their roots. Inoculation experiments showed that this was a correct assumption. Clusters of sclerotia from pure cultures were placed in contact with the taproots of 17 cotton plants grown in disease-free soil in iron drums, and 2 of these plants were killed. The same treatment on 55 cotton plants grown under field conditions, where no root rot had ever been in evidence, resulted in the infection of 9 plants; but only one of these died before the end of the season. Successful inoculations with sclerotia have been reported also by D. C. Neal from studies carried on at the United States San Antonio Field Station, San Antonio, Tex.

[1] Received for publication Dec. 11, 1930; issued June, 1931.

[2] KING, C. J., and LOOMIS, H. F. FURTHER STUDIES ON COTTON ROOT ROT IN ARIZONA, WITH A DESCRIPTION OF A SCLEROTIUM STAGE OF THE FUNGUS. Jour. Agr. Research 39: 641-676, illus. 1929.

[3] NEAL, D. C. THE OCCURRENCE OF VIABLE COTTON ROOT-ROT SCLEROTIA IN NATURE. Science (mis.) 70: 409-410. 1929.

[4] TAUBENHAUS, J. J., and EZEKIEL, W. N. OVERWINTERING AND SPREAD OF PHYMATOTRICHUM ROOT ROT. (Abstract) Phytopathology 20: 117. 1930.

On the other hand, 13 of 62 field-grown cotton plants were killed when inoculated with pure cultures of mycelia grown on dead root tissues, and 16 of 33 plants were killed when the inoculum consisted of sections of cotton roots from plants that had recently wilted from effects of the disease in the field. It was found in laboratory experiments that the mycelium from a germinating sclerotium was capable of extending a distance of 14 cm. through an unsterilized soil that was free from roots. These bodies, therefore, doubtless are capable of infecting plants without being in direct contact with their roots.

A further development from the inoculation studies conducted at Sacaton in 1929 was the success obtained in killing healthy plants with a pure culture of mycelia on dead cotton roots taken from a jar that had remained undisturbed in the laboratory for 11 months and in which no sclerotia were observed.

EFFECTS OF AIR DRYING, IMMERSION IN WATER, AND HEAT ON GERMINATION OF SCLEROTIA

In a previous paper [5] King and Loomis have reported that when relatively fresh sclerotia are removed from cultures, surface sterilized from 30 to 45 seconds in a 1:1,000 mercuric chloride solution, and incubated at about 25° C. on a suitable medium, 95 to 100 per cent of them may be expected to germinate.

Sclerotia that formed October 26, 1928, in a jar culture, were left undisturbed until November 7, 1929. On the latter date 46 of them were removed, placed on steamed rice in Petri dishes, and incubated at 25° C. After about 48 hours it was found that 42 of the 46 had germinated. To test the effects of drying, numbers of fresh sclerotia were removed from pure cultures and exposed to drying in the air for varying lengths of time. After drying they were placed on a culture medium and incubated. The germination results are shown in Table 1.

TABLE 1.—*Germination of sclerotia of Phymatotrichum omnivorum after drying in air for various periods*

Period of drying (minutes)	Sclerotia dried in air		Period of drying (minutes)	Sclerotia dried in air	
	Total	Germinated		Total	Germinated
	Number	*Number*		*Number*	*Number*
6	10	10	30	20	16
15	20	20	45	20	14
18	10	10	60	10	3
21	11	11	75	10	0
24	10	9	90	10	0

It will be noted that exposure to the air at room temperature for about 75 minutes was sufficient to kill these simple sclerotia. A longer period of drying would no doubt be required to destroy the large, compound masses of sclerotia that sometimes occur in cultures and in nature.

The results obtained by drying simple sclerotia in a desiccator containing sulphuric acid were similar to those shown above. All the sclerotia exposed to such drying for 60 minutes failed to germinate.

KING, C. J., and LOOMIS, H. F. Op. cit. (See footnote 2.)

It has been observed in repeated tests that sclerotia remain viable for long periods of time when immersed in distilled water. In one test, a quart-jar culture of sand and dead cotton roots, inoculated July 9, 1929, and containing a large number of sclerotia that had developed between July 18 and 24, was filled with distilled water to a point above the sand and roots and stored in the laboratory. Small numbers of sclerotia were removed from time to time thereafter for germination tests. In all the tests made during the first two or three months nearly all the sclerotia germinated. One test, made October 24, 92 days after the immersion treatment, resulted in the germination of 13 of the 16 sclerotia removed, or 81 per cent. However, a later test, made 121 days after the culture was submerged, resulted in the germination of only about 20 per cent of the sclerotia, and many showed signs of disintegration.

An indication of the sensitiveness of the sclerotia to heat was obtained by placing fresh sclerotia in test tubes of distilled water, which were then immersed in water baths with controlled temperatures. The baths in which the sclerotia were immersed for 15 minutes were maintained at temperatures ranging by 1-degree stages from 40° to 47° C. No definite loss of vitality was shown by immersion in the 40°, 41°, 42°, and 43° baths; but a distinct decrease in viability was evident after exposure to the next two higher temperatures (Table 2), and no sclerotia remained alive after immersion for 15 minutes in the 46° or 47° baths.

TABLE 2.—*Viability of sclerotia immersed for 15 minutes in uniform-temperature baths of 40° to 47° C.*

Temperature maintained (°C.)	Sclerotia tested	Sclerotia viable	Temperature maintained (°C.)	Sclerotia tested	Sclerotia viable
	Number	*Number*		*Number*	*Number*
40	15	14	44	40	24
41	15	13	45	40	14
42	15	14	46	25	0
43	30	27	47	10	0

In later experiments quart fruit jars were partly filled with moist sand, and a few sections of infected cotton roots about one-half inch in diameter and some simple sclerotia were placed in the center of the mass of sand. A thermometer was then inserted with the bulb in contact with the fungus material. The jars were placed in the water baths, where they were slowly heated until the temperature of the center of each jar reached the desired point, as indicated by the thermometer. The jar was then immediately removed and allowed to cool. The maximum temperature at the center of the jars ranged from 38° to 52.5° C. In most cases the maximum temperature was held from two to four minutes before the center of the jar began to cool. When the root sections and sclerotia were tested, it was found that a maximum temperature of about 43° was sufficient to kill the sclerotia, while a maximum temperature of about 51° was required to kill the mycelium on and in the root tissues.

EFFECT OF DISINFECTANTS ON GERMINATION OF SCLEROTIA

As solutions of formaldehyde have been used with a fair degree of success for several years in experimental control or eradication of root-rot infection in field crops, it seemed advisable to ascertain the susceptibility of the sclerotia to these solutions. A preliminary test was made under laboratory conditions to determine the strength of solution that would likely prove best suited for application in the field. Individual sclerotia of average size in lots of 10 were immersed for 30 minutes in solutions ranging from 1 per cent commercial formalin to as low as one-sixteenth of 1 per cent. In two tests, all sclerotia exposed in solutions of one-half of 1 per cent or less germinated, while of those tested in the 1 per cent solution, 2 of a total of 10 grew in the first trial and 3 of a total of 10 in the second. As might be expected, later tests indicated that when the period of immersion was lengthened the viability of the sclerotia was reduced.

To determine the effects of formaldehyde on sclerotia under conditions similar to those in the field, cylindrical cores of soil 1 foot in diameter and 1 foot deep were removed intact from the field in iron tubes. Commercial formalin solutions of 1 per cent and 1½ per cent were added to these cylinders of soil until they were saturated, and the excess solution was allowed to drain off. At intervals of 24 hours during the first four days and on the sixth day after disinfection, 10 fresh sclerotia, inclosed in slender cylinders of filter paper containing fine, dry sand, were introduced into each core of soil, and the treated soil was packed around them. The sclerotia were allowed to remain in the soil for three hours and were then removed, washed in distilled water, and tested for germination. All of the sclerotia subjected to this treatment failed to germinate.

Sections of infected cotton roots, about one-half inch in diameter, wrapped in filter paper, were inserted in the soil in the same manner and at the same time as the cylinders containing sclerotia. These were allowed to remain in the treated soil for 12 hours and were then removed and placed in moist chambers. Those placed in the soil during the first four days after treatment showed no fungus growth, but a growth of mycelium developed on those inserted on the sixth day, indicating that the strength of the formalin was not being maintained.

In order to study the lethal effects of formaldehyde gas on the fungus under various forms and conditions, an experiment was conducted as follows: Glass tubes 3 feet long and 1 inch in diameter were filled with moist sterile sand and inoculated at one end with a small section of infected root tissue. When the growing strands had advanced several inches through the sand, additional sections of infected root tissue and a number of sclerotial clusters of various sizes were inserted in the sand at various intervals in advance of the growing strands. A flask containing a solution of 1½ per cent formalin was then attached to one end of each tube and an aspirator was connected to the other end. The solution of formalin was heated slightly and the vapor was drawn through the tubes in which the fungus and sclerotia were exposed. Another set of tubes was set up in like manner, but water instead of the formalin solution was used as the source of vapor.

It was noted that the elongation of the strands in the tubes ceased soon after they were exposed to the formaldehyde gas, but was not

interrupted in the control tubes. At the end of 21 hours the sclerotia and root tissues were removed from both sets of tubes and placed in moist chambers and incubated. A growth of mycelium resulted from all the clusters of sclerotia and from all the root tissues removed from the control tubes, but no growth came from the sclerotia and tissues exposed to the formaldehyde gas. (Fig. 1.)

In another test, sclerotia in groups of 10 individuals were immersed for 30 minutes in solutions containing 1 part mercuric chloride to 1,000, 2,000, 3,000, 4,000, and 5,000 parts of water, and were tested for viability on steamed rice. None of the 10 sclerotia that had been placed in each of the two highest concentrations germinated, but of those subjected to the three lower concentrations, 3 or 4 in each culture of 10 developed growth.

As a further test other groups, also of 10 sclerotia, were immersed in a 1:1,000 mercuric chloride solution for periods of one-half, 1, 2, 3, 4, and 5 minutes. They were then removed, rinsed with sterile water, and tested for germination. In the four shortest periods of immersion the number germinating was 5, 2, 4, and 1, respectively, while no sclerotia germinated after being submerged for 4 or 5 minutes.

RELATION OF PERIODIC DEVELOPMENT OF SCLEROTIA TO LONGEVITY OF THE FUNGUS

In several cultures it has been observed that old clusters of sclerotia are sometimes regenerated by a budding process in which new sclerotia are formed. (Fig. 2.) Occasionally old strands may develop swellings and produce a few sclerotia in the same direct manner as new and actively growing strands, but more often the late-developed sclerotia appear to be an excrescent growth from old sclerotial structures. The growth of the nodular masses is sometimes more or less continuous for a long time, but in other cases there appears to be a period of quiescence in the entire culture which may last for several weeks or months. The renewed growth on the strands or sclerotia clusters is made evident by its whitish or pearly appearance in contrast to the dark or reddish-brown color of the old growth. The new portions when detached and tested show a much higher proportion of germination than the older portions.

TABLE 3.—*Number of days between date of inoculation and dates on which earliest and latest additions of growth were observed in the formation of sclerotial accretions in cultures of Phymatotrichum omnivorum*

Culture No.	Culture inoculated	Period after inoculation		Culture No.	Culture inoculated	Period after inoculation	
		First sclerotia observed	Last addition to old sclerotial clusters			First sclerotia observed	Last addition to old sclerotial clusters
		Days	*Days*			*Days*	*Days*
A-1	Sept. 20, 1928	37	240	145-1	Aug. 29, 1929	15	102
B-1	do	41	132	170-2	Sept. 11, 1929	12	242
9-2	Jan. 22, 1929	21	117	232-1	Nov. 6, 1929	19	185
16-1	Jan. 25, 1929	18	114	243-1	Nov. 18, 1929	11	99
17-1	do	18	114				

FIGURE 1.—Effect of formaldehyde gas on sections of cotton roots infected with *Phymatotrichum omnivorum*. Natural size. A, Root sections 7 days after removal from tubes of sand where they were exposed for 21 hours to a current of vapor from a 1½ per cent formalin solution. No root-rot strands have developed from the root sections. B, Root sections 7 days after removal from control tubes of sand where they were exposed for 21 hours to the vapor from water. Root-rot strands have originated from each root section

FIGURE 2.—New growth of root-rot sclerotia developed by a process of budding on old, compound sclerotial structures 230 days after the first portions of the mass were observed. The dotted line defines the limits of the old masses of sclerotia, and the arrow designates the new formations of growth. × 5

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It has not been determined how long this periodic production of new sclerotial material may continue, but it is not unreasonable to suppose that the process might be carried to the stage of a third crop, or even beyond. Under field conditions such a process would allow viable sclerotia to be present in the soil for long periods in the absence of the active hyphal forms of the fungus, so that practices of clean cultivation or the planting of nonsusceptible crops could not be relied upon to eradicate or control the disease.

Data on a number of cultures in which old sclerotia developed new portions are shown in Table 3.

The culture numbered 9–2 in Table 3 was prepared January 22, 1929, in a quart fruit jar containing moist sand and dead cotton roots, and cultures 16–1 and 17–1 were prepared in like manner on January 25. On February 12 these three cultures on which development of sclerotia had begun, three other fresh cultures which contained no sclerotia, and an old culture containing a single sclerotium were placed in a wooden box and buried in the field, so that the tops of the cultures were about 1 foot beneath the surface of the soil. On May 19 the cultures were removed, and the three named above, which contained new sclerotia when buried, showed recent development of sclerotia. The four other cultures showed no indications of recent growth. The lowest air temperature recorded near by during the period of exposure in the soil was 26° F. A germination test was made to determine the viability of the old dark-colored sclerotia, the reddish-brown type of intermediate age, and those newly developed, which were white or grayish in color, in the three cultures that contained the new sclerotia. None of the dark-colored individuals germinated, but a large proportion of the reddish-brown group and all the recently developed sclerotia were found to be viable.

GROWTH RATE OF STRANDS IN GLASS TUBES

Further studies were made on the growth of mycelial strands through long glass tubes, 1 inch in diameter, containing sand and soil. The daily progress through the tubes of sand was similar to that previously reported,[6] but longer tubes were used. Disease-free moist soil, removed from field plots adjacent to root-rot spots, was placed in some of the tubes without sterilization and a pure culture of the fungus introduced at one end of the tubes on a small piece of dead cotton root. The growth and behavior of the strands which resulted were similar to that noted in previous experiments with sterile soil. The daily measurements of strand growth were based on the elongation of the hyphae that were visible near the surface of the glass tube. A careful study of the behavior of the fungus in such tubes in previous experiments had shown that when moisture conditions were favorable the advancing hyphae made progress among the sand particles at about the same rate as along the glass surface.

In one test a glass tube 15 feet long, filled with moist, sterile sand, was used, and the fungus was introduced at one end on a piece of dead cotton root on June 19. At intervals of approximately 2½ feet throughout its length, spaces about 2 inches long in the tube were filled with pieces of sterilized dead cotton roots. The fungus began to progress through the tube from the inoculum on June 21, and on

[6] KING, C. J., and LOOMIS, H. F. Op. cit. (See footnote 2.)

June 26 a crop of sclerotia began to form on mycelial growth that developed between June 22 and 24. The next deposit of sterilized roots was completely enveloped on July 15, and on July 27 a second formation of sclerotia was observed developing on growth that had formed from July 19 to July 25, inclusive. The third deposit of cotton roots was enveloped on August 11, and on August 18 a third formation of sclerotia was noted on that part of the strands which developed between August 12 and 16. The next deposit of roots was passed September 2 without sclerotia being formed, but following the passage of the last deposit, about October 10 or 11, a single

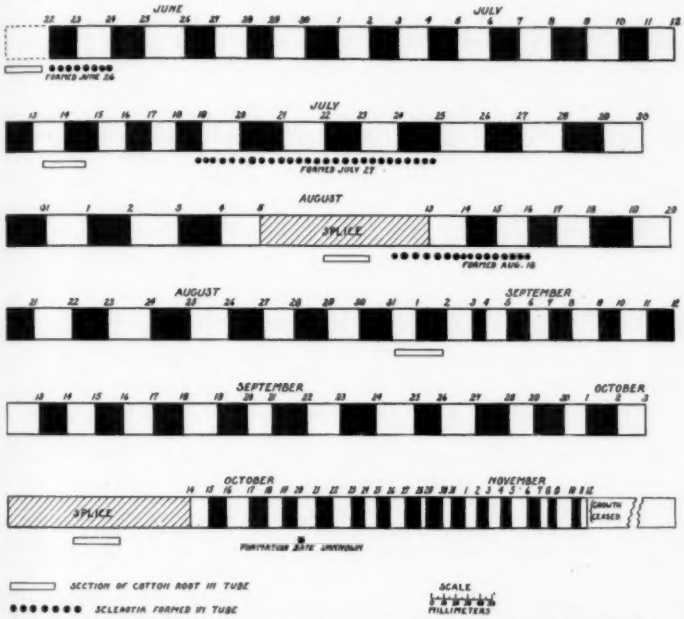

FIGURE 3.—Daily elongation of root-rot strands from June 22 to November 12, 1929, through a 15-foot glass tube, 1 inch in diameter, containing sand in which pieces of cotton roots were placed at intervals of approximately 2½ feet

sclerotium was formed on a strand developed October 20, although the date of its formation was not noted.

Elongation of the strands in this tube terminated on November 12, the strands having traversed a distance of 3,185 mm. in the 149 days, an average daily growth of a little more than 21 mm. A maximum daily growth of 37 mm. occurred twice during the test. A slight increase in the rate of elongation of the strands was noted several days after their terminal growth had passed the stored root tissues, and the increased rate was maintained even during the period when new sclerotia were being developed. A diagram of the daily elongation of the fungus in this tube, the location of the deposits of food, and the points at which sclerotia were formed is shown in Figure 3.

It appears significant that the strands in this and other tests began the development of sclerotia soon after having made contact with a

fresh food supply. Sclerotia have been observed in tubes of glass beads as far as 25 cm. from the nearest food material; but, as the strands become noticeably smaller on extending much farther than this, it seems probable that a diminution in the development of sclerotia may be expected as the distance is increased.

On the basis of early observations on the behavior of the fungus in alfalfa fields, it was reported that the mycelium showed a tendency to spread centrifugally from initial points of infection and only occasionally made an immediate reinvasion to attack plants sown in the area behind the advancing zone of infestation.[7] An effort was made to determine whether the mycelium, in its movement through the sand or soil, left anything in the nature of a toxic residue that would inhibit a second or third passage of the strands. Two glass tubes 3 feet long, containing sand that was permeated with root-rot hyphae and strands developed in August, 1928, were selected for the test. One of these was reinoculated on August 9 and the other on August 14, 1929, with infected cotton root tissues introduced at the same end of each tube as previously. By September 2 the strands had grown completely through the tube inoculated on August 14, a distance of 594 mm. in 19 days. By September 3 the mycelium had completed its passage through the tube inoculated on August 9, having grown a distance of 640 mm. in 25 days. The average daily growth in these tubes was 31.3 mm. a day. The same tubes were inoculated for the third time, without sterilization, on September 13, after the sand had been shaken to break up and obscure the old mycelia so that the growth of the new strands might be observed and measured more easily. The passage of the strands through the entire length of one tube was completed on October 24, and through the other on October 28. During the period when this third test was being conducted the temperatures were considerably lower than during the previous tests, and this factor, doubtless, accounted for the slower rates of growth, the average of which was 16 mm. and 13.2 mm. per day in the respective tubes.

In the light of the behavior of the fungus in these tubes it would not appear that the root-rot mycelium leaves any substance in the soil that is toxic to new fungus growth.

One interesting result of breaking up the strands by shaking the contents of the tubes before the third inoculation was the development of numerous hyphae from the ends of many of the broken fragments of the old strands. Other broken pieces of coarse strands, removed from sand in old cultures, were transferred to culture tubes containing root tissues, which were promptly enveloped by the resulting new growth. This behavior is in accord with Duggar's [8] belief that the strands are sclerotial in character. There appears, however, to be a great diversity in the size and structure of strands, which may govern their longevity, some forms in culture and in nature remaining viable much longer than others. The larger sclerotia appear to be longer lived than any of the strand forms so far observed.

In connection with the study of the mycelial strands in long glass tubes containing moist sand and soil, tests were made in which 2-mm.

[7] KING, C. J. HABITS OF THE COTTON ROOT-ROT FUNGUS. Jour. Agr. Research (1923) 26: 405–418, illus. 1924.

[8] DUGGAR, B. M. THE TEXAS ROOT-ROT FUNGUS AND ITS CONIDIAL STAGE. Ann. Missouri Bot. Gard. 3: 11–23, illus. 1916.

glass beads were substituted for the sand and soil so as to insure the complete absence of organic matter other than the inoculum. Sterile water was added until the beads were saturated, and the gravitational water was then drained away, leaving only film moisture, after which the tubes were inoculated with the fungus on sections of cotton roots. The rate of elongation of the strands through the beads was considerably slower than through the sand, but in some cases the growth continued for more than a month, and in one 2-foot tube the mycelium traversed a distance of 511 mm. in 31 days, the most rapid growth in a single day being 23 mm. In one of the six tubes of beads included in the test, sclerotia developed in great numbers on the strands throughout a distance of 250 mm. from the inoculum, and in one place their formation was almost continuous for a distance of 80 mm. A part of this tube containing a chainlike formation of sclerotia is shown in Figure 4, A, while a magnified view of a part of this formation is shown in Figure 4, C. A similar view of a section of another continuous formation in the same tube is shown in Figure 4, B.

The inoculum was removed from one tube of glass beads after the strands had grown a distance of 196 mm., and on the second day following this removal the growth rate slackened considerably; but the retarded growth was maintained for 13 days, during which time the strands extended a distance of 84 mm.

VARIATIONS IN VIGOR OF DIFFERENT ISOLATIONS OF THE ROOT ROT FUNGUS

Observations made on a group of 50 cultures, 10 of which were derived from a Texas type culture, 19 from an Arizona type isolated in 1929, and 21 from an Arizona isolation made in 1928, showed that the average number of days required for the first sclerotia to appear after inoculation was 8.8, 11.3, and 13.1 days, respectively.

Nearly all the sclerotia that developed in cultures containing cotton root tissues during September and October, 1928, were derived from a culture of the fungus that had been isolated the previous July. Early in 1929 cultures were obtained from two sources in Texas. One of these produced a vigorous growth of mycelium in all transfers, and on cotton root tissues almost invariably began to develop sclerotia within a few days. Transfers from the other culture developed very slowly, and no sclerotia were produced, although the fungus was kept alive for several months. It was reported that this culture had been maintained on artificial culture media for a long period.

Several new isolations from different areas of infection at Sacaton were made during the summer of 1929, and some of these showed even greater vigor and developed sclerotia more rapidly and abundantly than the isolation made the previous year. Some of the most rapidly growing cultures developed sclerotia within six days after the inoculum material was introduced into the containers, while in other cultures 16 days sometimes elapsed before they began to form. In some cultures, not included in the comparative-vigor tests, periods of 40 to 80 days have been known to elapse between inoculations on dead root tissue and the formation of sclerotia. In one culture inoculated with a sclerotium, 84 days elapsed before new sclerotia were produced.

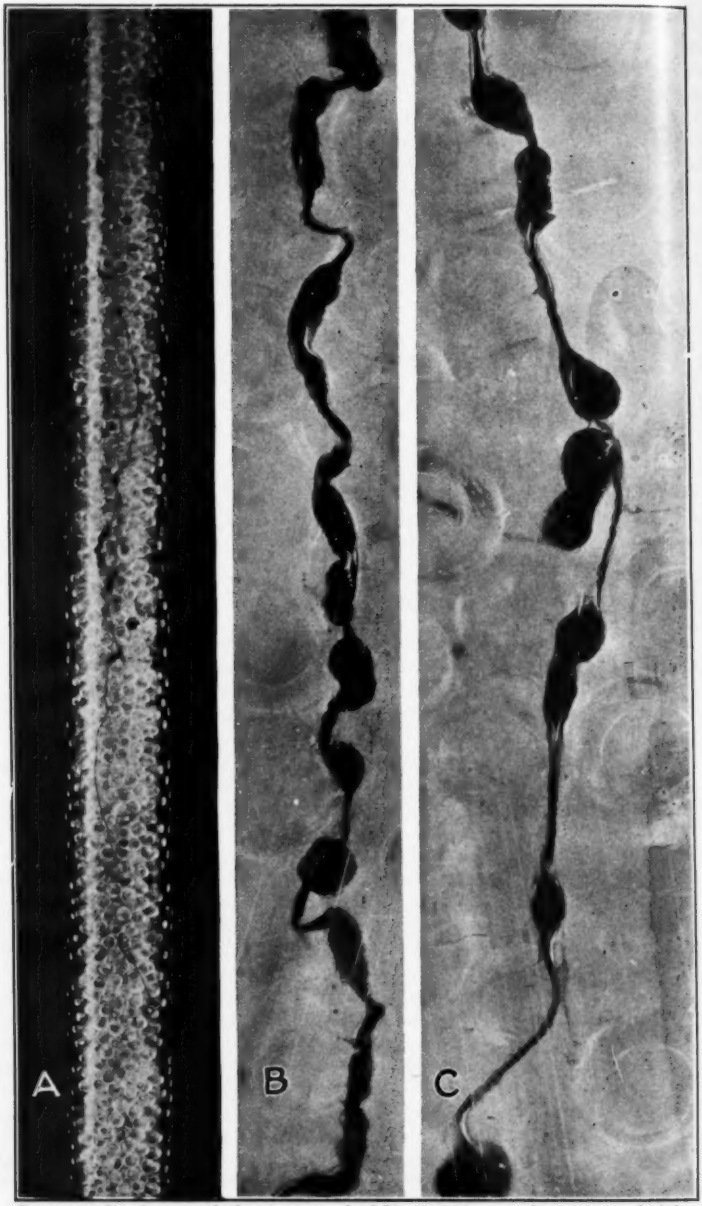

FIGURE 4.—Development of sclerotia on strands of *Phymatotrichum omnivorum* grown in tubes of moistened glass beads: A, Chainlike formation of sclerotia on strands in glass beads over 15 cm. from the root-section inoculum, which was the only food material in the tube (natural size); B, section of one of the strands from this tube, showing almost continuous formation of sclerotia (× 10); C, section of a portion of the strand visible in A, showing an almost continuous series of sclerotia (× 10)

In 1929, isolations were made from several areas in cotton fields where the disease was becoming increasingly destructive, and from other areas where the extent of damage had been decreasing for several years. The mycelium in cultures derived from the areas where the disease was most active appeared to be more vigorous than that from areas where the fungus was less destructive, but no definite conclusions could be drawn on account of the small number of cultures under observation.

The difference in behavior of cultures prepared from recent and from old isolations suggests that the fungus may decline in vigor after being maintained in the laboratory for many months.

SUMMARY

Inoculation experiments with sclerotia of the cotton root-rot fungus, *Phymatotrichum omnivorum*, showed that the disease could be communicated to healthy plants by these structures when stimulated by proper conditions.

Air drying for 1¼ hours in an open room or in a desiccator or immersion for 15 minutes in hot water at 46° C. was found sufficient to kill individual sclerotia.

Sclerotia immersed in distilled water were 81 per cent viable after 92 days, but after 121 days in water only about 20 per cent germinated.

When simple sclerotia and sections of infected cotton roots one-half inch in diameter were placed in the center of quart jars filled with sand and the jars immersed in water, a maximum temperature of about 43° C. maintained for two to four minutes was required to kill the sclerotia, while a temperature of about 51° was required to kill the mycelium on and in the root tissues.

Individual sclerotia were killed by a 1 per cent formalin solution and by a 1:2,000 mercuric chloride solution in about 30 minutes and by a 1:1,000 mercuric chloride solution in 4 to 5 minutes.

Sclerotia that were buried for 3 hours in large cores of undisturbed soil from 1 to 6 days after treatment of the soil with 1 per cent and 1½ per cent formalin solution were killed, and the mycelium on sections of infected cotton roots one-half inch in diameter, buried in like manner for 12 hours in the treated soil, was killed during the first 4 days after the formalin treatment, but that on the roots inserted the sixth day remained alive.

Root-rot sclerotia, exposed strands, and active mycelium on cotton root tissues, placed in glass tubes of sand, were killed when exposed for 21 hours to the gas liberated from a 1½ per cent formalin solution.

New sclerotia may be developed periodically in old cultures by a budding process on the surfaces of old sclerotial clusters, or directly from old strands, five or six months after the first sclerotia appear. It is indicated that the life of the fungus may be prolonged by this process.

In one experiment, root-rot strands during 149 days grew a distance of 3.2 meters (10.5 feet) through a long glass tube which contained moist sand with small deposits of dead root tissues placed at intervals of 2½ feet.

It was observed in this and other tests that there was a tendency for sclerotia to develop on the strands soon after they had advanced beyond a fresh food supply. Their development was not immedi-

ate on the new filaments, but usually they formed continuously for several days on the increments of strand growth several days old, between the food supply and the advance hyphae.

The ability of the strands to grow through long tubes of sand three times in succession without resterilization of the sand indicated that no toxic substances were left from the mycelium in the soil to interfere with subsequent growth when reinfected.

It was apparent that some types of root-rot strands are sclerotial in character and under favorable conditions remain viable for long periods.

In a 2-foot glass tube containing only small glass beads and distilled water, root-rot strands advanced a distance of 511 mm. in 31 days from the inoculum placed at one end and developed sclerotia in great numbers over a distance of 250 mm.

Some isolations of the fungus differed from others in vigor of growth and in the ability to develop sclerotia in great numbers. It is possible that differences in the behavior of spots of infection in the field may be explained by such variations.

There are some indications of staling in old root-rot cultures that have been maintained for long periods on artificial media.

DISPERSION OF SOILS BY A SUPERSONIC METHOD [1]

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INTRODUCTION

In attempts to remove the colloid from a soil quantitatively there are always evidences that the soil residue still contains some colloidal material. This fact is indicated by determinations of the heat of wetting, the absorption of water vapor, dye, or ammonia, or by microscopic examination of the noncolloidal fraction.[3,4] The colloid can be removed most readily, and probably most completely, by subjecting the soil sample to chemical treatments. In the mechanical analysis of soils by the international method, which is designed to give complete dispersion of the colloidal material, the sample is treated successively with hydrogen peroxide and hydrochloric acid, then washed with distilled water, and finally shaken with an alkaline deflocculent. It seems likely that the colloid extracted from a soil sample so treated would differ in physical and chemical properties from the colloid obtained from soil material dispersed by purely mechanical methods. It is evidently highly desirable to find some method of extracting colloids from soils as completely as possible without resort to chemical treatment, even though the extracted colloid may show alteration in properties due to the mechanical methods of dispersion.

When the remarkable dispersive effects produced by supersonic waves were first announced by Wood and Loomis [5] it was thought that these waves might be used to produce a greater dispersion of soil material than had hitherto been obtained by either physical or chemical means. Accordingly soil samples were submitted to the Loomis laboratory for test, and later, through the courtesy of Mr. Loomis, the supersonic equipment installed in his laboratory was placed at the disposal of the writer for further tests of the dispersive effects of supersonic waves on soil material. As a consequence of these favorable preliminary trials somewhat similar apparatus was installed in this bureau for use in making a comparison of the amount of colloid extractable by supersonic dispersion with that extracted by the hitherto most successful method of mechanical dispersion.

APPARATUS

The high-frequency, high-intensity waves of the longitudinal sound-wave type used in this investigation, which are called supersonic waves, were produced by a piezoelectric quartz crystal. Such a

[1] Received for publication Feb. 2, 1931; issued June, 1931.

[2] Acknowledgment is gratefully made of the assistance of Capt. E. G. Oberlin and members of the staff of the Naval Research Laboratory in designing and constructing the supersonic driver and in furnishing the piezoelectric quartz crystals; and of the assistance of Dr. C. H. Kunsman, of Fertilizer and Fixed Nitrogen Investigations, Bureau of Chemistry and Soils, in permitting the use of a 1,500-watt radio transmitter and other equipment, as well as in supplying laboratory space for conducting this investigation.

[3] GILE, P. L., MIDDLETON, H. E., ROBINSON, W. O., FRY, W. H., and ANDERSON, M. S. ESTIMATION OF COLLOIDAL MATERIAL IN SOILS BY ADSORPTION. U. S. Dept. Agr. Bul. 1193, 42 p. 1924.

[4] ANDERSON, M. S. THE HEAT OF WETTING OF SOIL COLLOIDS. Jour. Agr. Research 28: 927–935. 1924.

[5] WOOD, R. W., and LOOMIS, A. L. THE PHYSICAL AND BIOLOGICAL EFFECTS OF HIGH-FREQUENCY SOUND WAVES OF GREAT INTENSITY. Phil. Mag. and Jour. Sci. 4: (7). 417–436, illus. 1927.

crystal cut in a certain manner contracts when opposite electrical charges are applied to the opposite faces and expands when the charges are reversed. If the frequency of this alternating high potential is the same as the natural longitudinal frequency of vibration of the piezoelectric crystal, waves of high amplitude are generated, so that considerable sound energy is delivered by the crystal to the medium surrounding it. In this instance the alternating potential, roughly estimated at 25,000 volts, was supplied by a 1,500-watt vacuum tube oscillator tuned to the resonant frequency of the crystal. The crystal was immersed in an oil bath and its energy was transmitted through the oil into an Erlenmeyer flask containing a water suspension of the soil material to be treated.

The oscillator was adapted from a United States Navy transmitter installed in the high-tension laboratory of Fertilizer and Fixed Nitro-

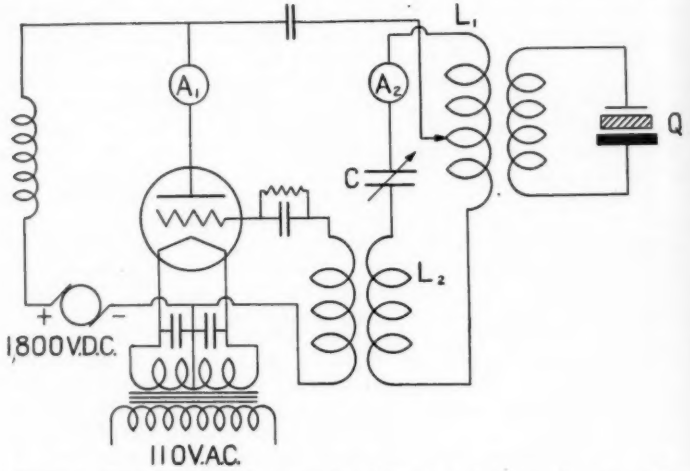

FIGURE 1.—Circuit diagram of the supersonic oscillator, A_1 and A_2, ammeters; L_1 and L_2, inductances; C, variable condenser; Q, quartz crystal

gen Investigations of the Bureau of Chemistry and Soils. A diagrammatic sketch of the circuit, which is the Hartley circuit, is shown in Figure 1, and the parts of the apparatus used are shown in Figures 2 and 3. The oscillator employed six 250-watt vacuum tubes in parallel. The filaments were heated by 60-cycle alternating current supplied by a low voltage transformer, and the plate current was supplied by an 1,800-volt direct-current generator. The inductances of the tuned circuit L_1 and L_2 (fig. 1) were made of edgewise wound copper ribbon. The capacitance C of the tuned circuit consisted of a variable air condenser connected in parallel with a fixed one. The circuit driving the crystal Q was inductively coupled to the plate coil of the oscillator L_1 by a single layer solenoid, consisting of about 300 turns of No. 28 double silk-covered copper magnet wire wound on a glass rod form having a diameter of 4 inches. The terminals of this coil were connected through large leads, in order to prevent corona losses, to the electrodes in contact with the quartz crystal.

The lower electrode was made of flat sheet lead about 1 cm. thick, upon which the quartz crystal rested. The upper electrode was made of sheet brass 0.03 mm. thick, and was cut slightly smaller in diameter than the quartz disk upon which it lay. The electrodes and crystal were placed in a small copper steam bath supported by the handles in a larger Pyrex crystallizing dish. (Figs. 2 and 3.) By this arrangement water could be run into the crystallizing dish to cool the contents of the steam bath. The quartz crystal and electrodes were covered to a depth of about 1.5 cm. with a high-grade transformer oil. The piezoelectric crystals used were flat circular disks of crystalline quartz about 8 cm. in diameter and 1 cm. and 0.85 cm. thick, respectively. Their vibration frequencies were, respectively, about 300,000 and 348,000 complete oscillations a second.

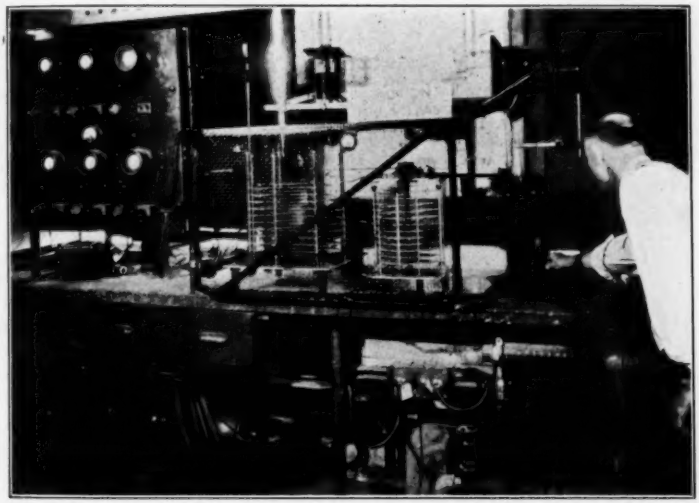

FIGURE 2.—Supersonic oscillator showing the vacuum tube control panel (left), the tuned driver circuit (center), and the radio frequency transformer and bath containing the piezoelectric crystal (right). Beneath the bench is the 1,800-volt motor generator set

When the oscillator was in operation the oil in which the quartz crystal was immersed became vigorously agitated and rose in a mound several centimeters above the crystal, giving the appearance of a fountain from which oil drops were frequently shot out for some distance. The soil material to be supersonically treated was placed in an extra tall Erlenmeyer flask to which water was added and the flask lowered into the mound of agitated oil. The maximum transmission of energy through the bottom of the flask from the oil into the soil suspension occurred when the bottom of the flask was parallel to the crystal face and certain distances away.

Boyle and Lehmann [6] have shown experimentally that Rayleigh's formula for the transmission of a train of plane sound waves

[6] BOYLE, R. W., and LEHMANN, J. F. PASSAGE OF ACOUSTIC WAVES THROUGH MATERIALS. Roy. Soc. Canada, Trans. 21 (pt. 1, sec. 3): 115–125, illus. 1927.

through a partition holds for supersonic waves. According to Rayleigh, the sound transmission is greatest when the thickness of the partition (Pyrex glass in this case) is an integral number of half-wave lengths. At a frequency of 348 kilocycles a half-wave length of sound in Pyrex glass is about 7.5 mm. Since it was not convenient to make an Erlenmeyer flask with its bottom of this thickness, it seemed preferable to approximate zero thickness as closely as possible. Accordingly, a flask was made whose bottom was flat, about 0.7 mm. thick, and about 1 cm. smaller in diameter than the quartz crystal.

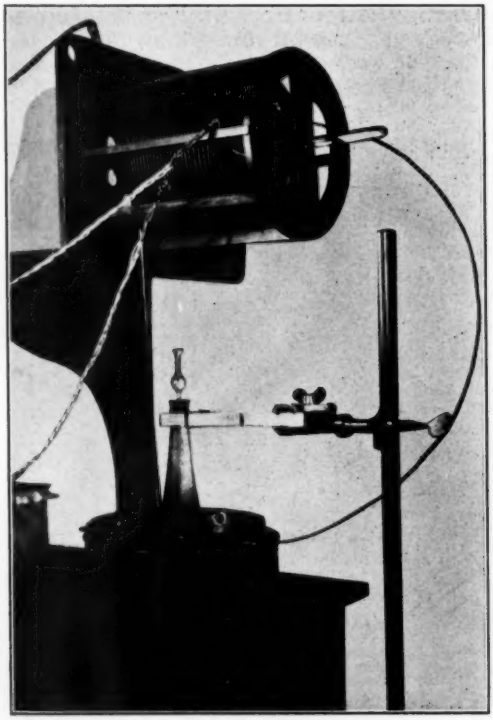

FIGURE 3.—Larger view of the radio frequency transformer and the bath containing the crystal in operation. In the flask may be seen the disturbed soil suspension and, on the inner walls, some of the standing waves

Of much more importance than the thickness of the flask bottom is its position. The flask should be so held that its bottom is parallel to the face of the quartz disk and at such a distance that waves reflected from the glass surface strike the quartz plate in phase with its own vibration. This allows wave trains of large amplitude and high energy to build up in the oil by multiple reflections and eventually to transmit this energy to the material in the Erlenmeyer flask.

A thick plate of high-density material (lead) was used for the lower electrode in order to reflect as much energy as possible up through the crystal. The electrode lying on the upper surface of the crystal was made of the thinnest available metal (brass shim) in order to interfere as little as possible with the upward transmission of energy in the oil. The flask was held by a wooden test-tube clamp attached to a laboratory tripod stand. The tripod base was provided with leveling screws, and the support rod was made of bakelite in order to avoid spark discharges to the hand when adjustment of the leveling screws was necessary.

When subjected to supersonic treatment the suspension in the Erlenmeyer flask appeared to boil violently. Usually a spray of fine drops filled the flask, resembling condensing steam. In the flask shown in Figure 3 may be seen the agitated soil suspension from

which standing waves of liquid gather on the inner walls of the flask. An opening was provided in the stopper to release air and water vapor without losing soil material. The crystal, oil bath, and suspension all heated rather quickly, the crystal having much the highest temperature. The oscillator was seldom run for periods longer than two or three minutes without cooling the oil bath and crystal. The heating of the suspension is due in part to the fact that the viscosity of the liquid increases as the square of the frequency, and in part to the rapid movement of the suspended particles through the liquid and their collisions while in motion. Under the most favorable conditions a suspension in the flask can be heated from room temperature to 100° C. in about two minutes. Water alone heated more slowly. The most rapid temperature rise recorded was that of about 40 c. c. of water containing blue-green algae, whose temperature rose from 18° to 68° in 30 seconds.

PROCEDURE

Air-dry soil samples of 10 to 30 gm., which had passed through a screen with round holes 2 mm. in diameter, were put into the special Erlenmeyer flask and from 50 to 125 c. c. of distilled water were added. The flask was then clamped in position about 1 to 2 cm. above the upper face of the piezoelectric crystal and its height adjusted by means of tripod leveling screws to give maximum transfer of energy to the contents of the flask. This position was determined either by observing the violence of agitation of the material within the flask or, better, by adjusting for minimum reading of the ammeter, A_2, in the oscillator circuit.

After supersonically shaking the sample for 2 minutes, the silt and clay in suspension were decanted through a 300-mesh screen into a 500 c. c. centrifuge bottle. Additional decantations were made until the centrifuge bottle was filled. The soil material remaining in the flask was again supersonically shaken, and the silt and clay was poured off until the sands appeared to be free from colloid coatings. With the soils used this usually did not require more than four or five supersonic treatments.

The silt and clay material was centrifuged at 325 gravity until only particles 1μ or less in diameter remained in suspension. This colloidal suspension was siphoned into a 1-liter assay flask. The water, carrying some material in solution, was removed by a Pasteur-Chamberland suction filter, the colloid being left in the flask. The sediment in the centrifuge bottle was shaken by hand, the bottle was filled with distilled water, again centrifuged, and the suspension siphoned off. When, after repeated centrifugings, the yield of colloid began to decrease, the silt and clay residue was transferred to the Erlenmeyer flask and supersonically shaken. Centrifugation and supersonic treatment were repeated until the yield of colloid decreased to a low value.

In order to secure a comparative basis for the effectiveness of the supersonic method of dispersion, duplicate samples were dispersed by rubbing. These samples were boiled, rubbed with a rubber "policeman," and decanted repeatedly until no further yield of silt and clay could be obtained from the sands. This separation usually required 15 or more 2-minute rubbings, as compared with four or five

shakings by the supersonic method. The colloid was separated in the same manner in both the rubbing and the supersonic methods. Both samples were centrifuged, as far as possible, at the same time, in order to secure the same size separations. When the yield of colloid in the rubbed sample began to decrease, the suspension remaining in the centrifuge bottle after siphoning the colloid was poured off. The sediment was dried to a moisture content near the sticky point. It was then rubbed, kneaded, and worked with a rubber policeman. Further separations by means of centrifuging and rubbing were continued until the yield of colloid fell to a low value.

EXPERIMENTAL RESULTS

Table 1 gives the results of the separations obtained by the two mechanical methods of dispersion, and also the results of mechanical analyses by the pipette method, of five soil types.

TABLE 1.—*Mechanical analyses of five types of soils, using three different dispersion methods*

Sample No.	Soil type and source	Depth	Dispersion treatment	Percentage composition		
				Sand	Silt	Colloid
		Inches	Chemical [a]	50.5	35.5	14.0
3405	Chester loam, Maryland	30–42	Rubbing	52.0	30.9	17.1
			Supersonic	45.3	36.8	18.0
			Chemical	67.0	2.8	30.2
4251	Norfolk sandy loam, Alabama	38–49	Rubbing	68.4	3.7	28.9
			Supersonic	66.6	3.1	30.3
			Chemical	11.4	28.0	60.6
4427	Iredell loam, North Carolina	10–20	Rubbing	16.3	18.1	65.6
			Supersonic	15.0	20.4	64.6
			Chemical	43.8	17.2	39.1
186	Cecil clay loam, Georgia	9–18	Rubbing	44.8	14.6	40.6
			Supersonic	45.7	12.9	41.4
			Chemical	16.9	29.1	54.0
4440	Davidson clay loam, NorthCarolina	9–36	Rubbing	18.4	23.7	57.9
			Supersonic	14.7	25.6	59.7

[a] Analyses by the pipette method.

In the mechanical methods of separation the upper limit of colloid size was between 1μ and 2μ in diameter. In the pipette method the separation was made at 2μ. The material listed as silt comprises all particles with diameters between 50μ and 2μ, that is, it consisted of all the silt and some coarse clay. In the pipette method used by this bureau[7] the organic matter is removed by hydrogen peroxide. The organic matter was not removed in the rubbing and supersonic methods, but the quantity was small in all samples. In the pipette method, dispersion was obtained by shaking with sodium hydroxide in the Cecil and Davidson samples, and the other samples were dispersed with sodium oxalate. On an average, the supersonic treatment yielded about the same amount of sand as the chemical treatment but less than the rubbing treatment.

Except in the Norfolk sandy loam, both mechanical methods yielded less silt and more colloid than did the pipette method. The samples from the Chester B_2 horizon were rich in flakes of partly

[7] OLMSTEAD, L. B., ALEXANDER, L. T., and MIDDLETON, H. E. A PIPETTE METHOD OF MECHANICAL ANALYSIS OF SOILS BASED ON IMPROVED DISPERSION PROCEDURE. U. S. Dept. of Agr. Tech. Bul. 170, 23 p., illus. 1930.

decomposed mica, which appeared to have been broken down into smaller particles by mechanical treatments.

The Cecil and Davidson soils are lateritic in character, and apparently have many colloid particles cemented into aggregates. Both soils flocculated quickly while being centrifuged. Very small quantities of colloid remained in suspension at the end of 20 minutes in the centrifuge when distilled water with a hydrogen-ion exponent of 6 or less was used to suspend the material in the centrifuge bottles. When just enough ammonia was added to the distilled water supply to bring it to neutrality, the amount of colloid remaining in suspension after centrifuging was abundant. In making the colloid separations of the Cecil and Davidson samples brom-thymol blue, put into the filter flasks, was used as an indicator and assisted in maintaining the suspension at about pH 7. If the material could have been centrifuged quickly in a continuous flow, high-speed centrifuge, it is possible that the colloid could have been separated with the addition of little or no ammonia. With the equipment available it was necessary for the material to remain deflocculated at least 20 minutes. Although ammonia was necessary for temporarily maintaining dispersion, it was not essential for obtaining it. Strictly speaking, these two methods of extraction are not purely mechanical.

The addition of ammonia to the silt and colloid suspensions of the other samples, although not necessary for separation of the colloid, greatly increased the yield and shortened the time required for a separation. For these three soils, the Iredell, the Chester, and the Norfolk, enough ammonia was used to give the water removed in concentrating the colloid a pH value of about 6.4 to 6.8.

The use of a small amount of ammonia as a deflocculent probably did not increase the total yield of colloid, but it did lessen the number of pourings required to make a separation. The number of centrifugings varied from about 30 for the Norfolk to about 90 for the Cecil and 120 for the Davidson when dispersion was obtained by rubbing. About the same degree of separation was obtained with half as many centrifugings when the samples were supersonically shaken. The exact number of operations is not significant because it varies with the amount of rubbing or supersonic treatment, the acidity of the suspension medium, the amount of shaking used in resuspending the sediment in the centrifuge bottles, and the duration of time of centrifuging. Because of the large number of operations involving many transfers of small amounts of material to and from large containers, the methods of separation do not favor high accuracy in the final quantitative results.

Some further difficulty was experienced in making the colloid separation. When the centrifuge was slowing down to a stop the bottles turned from a horizontal to a vertical position, causing a cyclonic motion to the suspension within, which stirred up some of the finest sediment in the bottom of the bottles. Because of this action it is likely that the upper limit of colloid size was nearer 2μ than the estimated 1μ in diameter.

In order to determine to what extent the soil particles were abraded by supersonic treatment, mechanical analyses were made of four samples of a Norfolk fine sandy loam subsoil. This soil was chosen because it had a desirable range of particle size distribution, was low

in organic matter, and was easily dispersed. The results are given in Table 2. Samples A and B are untreated duplicates and serve to indicate the accuracy of analysis. Sample C was given supersonic treatments for periods totaling 30 minutes and sample D was similarly treated for 60 minutes. All samples were shaken with the same amount of deflocculent, and analyses were made by the pipette method. The results all check within the accuracy of sampling and of analysis with the possible exception of the clay and colloid fractions. The colloid determination is usually the most accurate, and the silt, which is determined by difference, is the least reliable. It is possible that colloid coatings were more completely removed from the sand and silt fractions and more aggregates of coarse clay were broken down by supersonic treatment, but there is no indication of grinding of the sands. Sample C was shaken in a smaller flask than was D and may possibly have had as drastic treatment in 30 minutes as was given sample D in 60 minutes. The apparatus can be adjusted only to the maximum apparent activity.

TABLE 2.—*Mechanical analysis by pipette method of a Norfolk fine sandy loam subsoil* [a] *made to determine soil-particle abrasion by supersonic treatment*

Sample	Percentage composition							
	Sand of particle sizes indicated					Silt	Clay	Colloid [b]
	2.0 to 1.0 mm.	1.0 to 0.5 mm.	0.5 to 0.25 mm.	0.25 to 0.1 mm.	0.1 to 0.05 mm.	0.05 to 0.005 mm.	<0.0005 mm.	<0.002 mm.
A [c]	0.5	2.6	3.8	15.2	18.9	33.0	26.0	21.7
B [c]	.5	2.5	3.7	14.9	19.7	32.3	26.3	21.5
C [d]	.5	2.6	3.5	14.9	19.5	32.0	26.9	23.5
D [e]	.7	2.6	3.7	14.6	19.7	31.7	27.0	22.3

[a] Analysis by Hubert W. Lakin and Thomas M. Shaw.
[b] Included in the clay.
[c] Untreated duplicate.
[d] Treated supersonically for 30 minutes.
[e] Treated supersonically for 60 minutes.

In the foregoing experiment the entire sample was treated supersonically without making any separations of the finer material. In obtaining the results shown in Table 1 the sands were removed after the first few minutes of treatment and additional supersonic shaking was given to the silt and undispersed clay fractions. The supersonic treatment of the silt fraction probably was not so effective as when larger sand grains were present. As soil particles decrease in size, their momenta correspondingly decrease. On the other hand, the influence of the water films surrounding the particles increases with decreasing size until finally the particles subject to supersonic treatment are no longer able to break through the films and collide with other particles, or strike the walls of the containing vessel. The presence of the sands should aid in the removal of colloidal films from the silt grains and in the breaking apart of fine colloidal aggregates. Just how much of the effectiveness of supersonic treatment is due to actual collision of particles, how much to their large and alternating positive and negative accelerations, and how much to the turbulent flow of the suspension medium, is problematical. The viscosity of

water subjected to periodic compressional waves varies directly as the square of the wave frequency.

It is comparatively easy to cause grinding of sand grains in the rubbing method, and for this reason the rubbing was gently done in an excess of water during the process of separating the sands from the silt and clay. A microscopic examination of the sands revealed some colloid coatings on the rubbed sands but practically none on those supersonically shaken. On the other hand, it seems likely that abrasion caused by rubbing the silt and clay fraction in the centrifuge bottles by a rubber policeman reduced the quantity of silt. When the moisture content of the silt and clay mixture is reduced sufficiently it becomes rather stiff so that a heavy pressure can be applied with the rubber policeman. This method, under favorable conditions, is surprisingly effective in dispersing the colloid fraction.

In making the mechanical separations of the Cecil and Davidson soils, 30-gm. air-dry samples were used, and an attempt was made to fractionate the colloid. These fractions were not based on size separations but on the ease with which the colloid was dispersed. The first and largest fractions were obtained without rubbing or supersonically treating the silt fraction, although the sands were first cleaned by such treatments. When the yield of colloid decreased to a relatively low value, the material separated out was dried, weighed, and labeled "first fraction." The silts were then rubbed and supersonically shaken, respectively, a number of times, until the yield of colloid after treatment was small. The colloid so removed constituted the second fraction. The third and smallest fraction comprised the colloid subsequently removed by more vigorous and prolonged dispersion treatment. The colloid separation even then was not complete. A small and decreasing yield was obtained so long as the dispersion treatments were continued, with no indication of an end point such as occurs in the separation of silt and clay from sand by decantation. The removal of the third fractions to the extent obtained here required as many pourings as and more dispersion treatments than were required for the first and second fractions combined. The total amounts of colloid extracted from the Cecil and Davidson soils are given in Table 1, and the relative amounts of the different fractions are given in Table 3.

TABLE 3.—*Relative amounts of colloids fractionated from samples of Davidson and Cecil clay loams*

Soil type	Percentage of colloids in—					
	Rubbed sample, fraction No.			Supersonically shaken sample, fraction No.		
	1	2	3	1	2	3
Davidson clay loam	64	20	16	58	27	15
Cecil clay loam	75	22	3	75	20	5

The quantity of some fractions of extracted colloid was too small for making extended physical tests, so that only water-vapor absorption determinations were made. Air-dry samples were exposed in vacuum

desiccators at reduced pressure for five days to an atmosphere in equilibrium with a 3.3 per cent sulphuric acid solution at 35° C. The quantities of water vapor absorbed per gram of material are given in Table 4 for the silt and colloid of the Norfolk and Iredell soils, as well as for the silt and fractionated colloid of the Cecil and Davidson soils.

TABLE 4.—*Water vapor absorbed per gram of material over 3.3 per cent sulphuric acid*

Soil type	Rubbing treatment				Supersonic treatment			
	Colloid fraction No.			Silt	Colloid fraction No.			Silt
	1	2	3		1	2	3	
	Gm.	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*
Davidson clay loam	0.306	0.313	0.238	0.044	0.295	0.315	0.237	0.043
Cecil clay loam	.233	.228	.140	.013	.221	.254	.123	.013
Norfolk sandy loam	.272			.037	.273			.016
Iredell loam	.289			.024	.289			.024

These determinations were made primarily for the purpose of ascertaining whether the colloid obtained by the two methods had been differentiated by the processes of separation. The first fractions of both the Davidson and the Cecil colloid were removed with just sufficient dispersion treatment to clean the sands of colloidal material. Consequently their water-vapor absorptions by the two dispersion methods should check approximately. It is in the second and third colloid fractions of the Cecil and Davidson soils and in the total colloids of the Norfolk and Iredell soils that the water-vapor absorptions might be expected to show differentiations due to the methods of separation. The data show no such differentiation. Determinations of the water-vapor absorption of some of the separates over 30 per cent sulphuric acid gave as close agreement between fractions obtained by the two methods as between duplicates of the same fraction. The absorptive capacity of the third fraction is considerably lower than that of the first and second. The last small amount of material removed with the most drastic treatment, which constitutes the third fraction, probably contains more broken pieces of cemented aggregates and a relatively smaller amount of fine colloid, and should not be expected to have so high a water-vapor absorption. The term "colloid" as used here was intended to include all soil particles smaller than 1μ, whether original soil minerals or products of decomposition. Because of the methods of separation the upper size limit, however, is probably nearer 2μ.

The water vapor absorbed per gram of silt ranged from approximately 5 to 15 per cent of that of the corresponding colloid. Since the specific absorption of pure silt is probably very low the absorptive capacity of the silt fractions should indicate whether colloidal material is still present in those fractions, except for the presence of organic matter. Both colloid and organic matter are known to be present in small amounts. Here again the water-vapor absorption data indicate that the two methods were about equally effective in removing colloid from the silt fractions, although from a qualitative

comparison of the colors of the material and a microscopic examination of the silt grains, the supersonic method appeared to give the better dispersion. Although the sands were rubbed gently in excess water, the silt fractions were rubbed vigorously at such low moisture content as to allow comparatively heavy pressure to be applied to the plastic mass. One may conclude from the data of Table 1 that rubbing caused some grinding of the silt grains. Qualitative observations indicated that if the silts had been rubbed at a higher moisture content, in which condition less pressure is required to work the mass, much less colloid would have been removed, or, at least, more rubbing would have been required. As a consequence of the writer's experience during the prosecution of this work, his respect for the rubbing method has greatly increased, when the operation is carried out with silt and clay materials in a moderately stiff plastic condition.

The advantage of the supersonic over the rubbing method of dispersion lies in the greater ease with which it may be carried out. The number of supersonic shakings is about half the number of rubbing treatments, and the time required is even more favorable to the supersonic method. It takes much longer to dry down the material in a centrifuge bottle to the sticky point and rub it thoroughly than it does to transfer it to an Erlenmeyer flask and shake it supersonically.

A disadvantage of the supersonic method is that considerable expensive equipment is required to build the piezoelectric oscillator. The piezoelectric quartz plates, large enough to furnish sufficient energy, must be cut fron large quartz crystals, free from twinning and flaws and capable of withstanding rapid temperature changes and mechanical shock without shattering. Such quartz plates are not plentiful. Another disadvantage is that only small samples, probably not larger than 50 gm., can be effectively treated at one time with crystals of the size used and the power available. When the rubbing is done on large samples the hands may be used instead of a rubber policeman. The fine ridges of the palms of the hands are said to be very effective aids in the dispersion of soil colloids.

Both methods gave as good dispersion as the usual routine method of mechanical analysis which employs chemical aids. Although both rubbing and supersonic shaking are effective in securing dispersion, they can not maintain it. Either a separation must be made before flocculation occurs, which in the Davidson and Cecil soils is only a few seconds, or a chemical deflocculent must be used.

SUMMARY

A method of dispersing soil material by means of supersonic waves is described. A soil suspension is shaken by high-frequency, high-intensity sound waves produced by a large piezoelectric quartz crystal which is driven by a 1,500-watt vacuum-tube oscillator. The percentage of colloidal material extracted from soils by the new method is about the same as is secured by a rubbing method and is slightly greater than the percentage obtained from analyses by the pipette method. In neither the supersonic nor the rubbing method of dispersion was the extraction complete. A small and decreasing yield of material of colloidal size was obtained as long as the extraction

processes were continued. The results, however, are much more quickly and easily obtained by the supersonic method.

Determinations of the water vapor absorbed over 3.3 per cent sulphuric acid by the silt and colloid fractions showed no differences between the material extracted by the two methods. The water vapor absorbed per gram by the silt fraction ranged from 5 to 15 per cent of the absorption of the corresponding colloid.

PREDICTING GAINS IN FEEDER CATTLE AND PIGS[1]

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INTRODUCTION

Biometrical studies of data from group-feeding experiments with farm animals have generally shown a large amount of variation in the response of different animals in the same lot to what were supposed to be the same conditions of feed, housing, and care. Thus Mitchell and Grindley (*8*)[4] in an extensive study found coefficients of variability of individual gains to average about 21 per cent for sheep and 17 per cent for swine and steers. With variations as large as these they calculate that it would require 31 sheep per lot or 20 swine or steers per lot to prove (in the statistical sense) the reality of the difference when one lot makes gains 10 per cent greater than those of the other lot. Not only are most experimental lots smaller than these, but most observed differences in gains are also less than 10 per cent, except where the rations to be compared are so very different that the experimenter is fairly certain in advance which is the better.

This high variability in gains is sometimes inferred to be an index of the amount of experimental error attaching to all findings from group-feeding experiments. However, the conclusions drawn from feeding experiments are based not on average gains alone but also on average feed consumption, average quality of the final product, and various ratios or other combinations of these three kinds of primary data. The most appropriate statistical procedure for testing the validity of conclusions drawn from group-feeding experiments seems to be Student's method (*1*) applied to the conclusions drawn from several repetitions of an experiment.[5] This method can not be used until the experiment has been repeated at least once, and more and more repetitions will be required to prove the reality of smaller and smaller differences between the values of the rations tested. This method makes no direct use of individual gains. It is often desirable to estimate the significance of observed differences, at least in a tentative way, before an experiment has been repeated often enough to permit Student's method to show the full reliability of the conclusions. Variation in gains is the most accessible basis for such estimates, although much could be accomplished by also taking into account variation in quality of the final product as revealed by individual slaughter or carcass grades or appraisals. Variation in feed consumption can not of course be known in group-feeding experiments.

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[2] The writer is greatly indebted to the following members of the college, station, or extension staffs of the Agricultural and Mechanical College of Texas for making the estimates on which this report is based: G. W. Barnes, R. E. Dickson, E. R. Eudaly, W. E. Flint, C. B. Godbey, J. A. Gorman, Fred Hale, W. R. Horlacher, J. M. Jones, J. H. Knox, A. K. Mackey, W. L. Stangel, D. W. Williams, and R. H. Williams.

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[4] Reference is made by number (italic) to Literature Cited, p. 881.

[5] For an example of this method applied to feeding data, see Jones and Lush (*5*).

When the variation in gain is to be used as an index of the amount of experimental error it should be kept in mind that at least three factors other than errors of sampling may cause the calculated standard deviation of gains within a lot to be relatively larger than the real experimental error with which the differences should be compared. The first is the fact that initial and final weights are not exactly correct because of differences in "fill," undetected minor differences in health at weighing time, etc. Such errors cause the apparent standard deviation to be larger than the standard deviation of the true gains would be if these could be obtained free from such errors. The observed standard deviation can be corrected (*10*) roughly for this source of error. When such corrections are made it becomes apparent that this source of error usually accounts for only a small part of the observed standard deviation,[6] although it will assume considerable importance when the feeding periods are short and when inital and final weights are taken on only one day. It is probably of more importance with ruminants than with swine.

The second factor tending to magnify observed standard deviations of gains is inequality in feed consumption within a lot. To the extent that the steer or pig which made the high gains in a lot did so directly because it ate more feed than its per capita share, the standard deviation of the observed gains will be larger than it would have been if each steer or pig had eaten exactly the average ration for its lot. The importance of this depends primarily upon how high the correlation is between individual feed consumption and individual gain in the usual feeding experiment. The principles of nutrition lead one to expect that such correlations will usually be high, although doubtless quite variable from one experiment to another. It seems likely that this factor is of considerable importance in making the apparent probable error of feeding experiments higher than the error which should be used when gains are considered in relation to feed consumption, as is nearly always the case.

The third factor tending to magnify the observed standard deviation of gains is the fact that the experimental animals are not divided into lots by a random method but are more or less carefully balanced with respect to weight, breed, sex, age, and their conformity to the standard of excellence which the man in charge of the experiment has in mind. Sometimes even body measurements are taken into consideration in this balancing process, and, in the case of pigs, each litter is distributed evenly among the lots. Not all these factors receive equal attention. Weight is the primary basis of allotment in most cases. After the allotment by weights has been completed, the man in charge of the experiment usually studies each group and switches a pair of animals here and there between two lots until he is satisfied that the lots are as nearly equal as possible in market desirability, degree of finish, quality, and ability to gain weight. This

[6] For example, in one Texas feeding experiment the apparent standard deviation of total gains (based on 51 degrees of freedom) was 45.4 pounds for steers fed for 114 days and weighed three times at the beginning and end of the experiment. If a standard deviation of 10 pounds be assumed for the accuracy of single weights, the true standard deviation will be 44.7 according to Shewhart's formula: $(45.4)^2 = 2 \times \frac{(10)^2}{3} + (44.7)^2$.

It may be that 10 pounds is too small a figure for the error of single weights. It corresponds closely to the findings in studies of the day-to-day variation in live weight but would not include fills or shrinks extending over several consecutive days, as might result from a digestive disturbance or some other variation in health which, while temporary, would normally extend over more than one day. See Maymone and Sircana (7).

balancing according to judgment is frequently done in the case of steers, but less often with swine, where litter and age distribution assume much importance. Very little of this balancing according to judgment is done in feeding experiments with sheep.

The purpose of all this balancing is to make sure so far as possible that a high-gaining animal in one lot will be matched by an equally high-gaining animal in every other lot, and that a low-gaining animal, or one undesirable on the market, if present in one lot will be matched with an animal as nearly like it as possible in every other lot. If this procedure is successful, then the standard deviation of gains within lots will be kept larger than it would be if the animals were divided into lots purely at random. The importance of this balancing will depend upon the extent to which it actually achieves its purpose. This is the subject of the studies reported herein.

The problem may be stated in the form of three questions: (1) To what extent are differences in feed-lot gains and in market desirability correlated with differences in initial weight? (2) To what extent can the animal husbandman in charge of an experiment foretell which individuals will make the better and which the poorer gains? (3) To what extent can he predict the difference in market desirability which will exist between the animals when they are fattened?

NATURE AND SOURCE OF DATA

The animals used were steers that had been fattened during three years at substation No. 7 of the Texas Agricultural Experiment Station at Spur, and two years at College Station, and pigs from three feeding experiments carried on in different years at substation No. 10 at College Station.

The feeding of the pigs and steers was determined by the requirements of the projects in which they were used. After the animals had been divided into lots in accordance with those projects, the animal husbandman in charge and several of his associates rated each animal according to the amount of gain which he believed that animal would make relative to the average of its lot or relative to the animal which he believed would make the best gains in that lot. In three of the steer experiments an estimate was also made of what each animal would be worth per pound of live weight when the fattening was over. All the estimators were men trained in animal husbandry, and they occupied positions requiring constant contact with matters relating to animal husbandry. Several of them regularly taught classes in stock judging, and some have, from time to time, judged at State and prominent regional fairs.

In the second steer experiment each animal was rated in terms of the average of his lot. That is, a steer which was expected to gain 6 per cent more than the average of his lot was rated at 106 and one which was expected to gain 10 per cent less than the average of his lot was rated at 90. This, however, seemed to most of the men rather artificial and contrary to their natural method of judging. In all other experiments each man first picked out the individual which he thought would make the largest gain in the lot and this animal was given a rating of 100. Then he picked out the individual which he thought would make the second largest gain and rated it 98 or 95, or whatever percentage of the first one's gain he thought the

second would make. This was continued until every animal in the lot was rated. Then the next lot was rated with reference to the animal in it which was expected to make the largest gains. This was continued until all lots in the experiment had been rated. Some men worked rapidly and rated as many as 40 animals in little more than an hour. Others took more time and some made a tentative rating one day and returned to revise it a day or two later. Except in the first pig experiment, each man was requested to work independently of the others and to take as much time as he felt would be necessary to make the best possible estimates. In the first pig experiment the three men acted as a committee, consulted freely and turned in only a single set of estimates. All estimates were given to the writer within two weeks after the beginning of each experiment and before any intermediate weights were taken.

The experiments with pigs were ration tests made under the direction of Fred Hale. All rations were reasonably good. All gains were likewise good, the pigs averaging more than 1.5 pounds per head per day in all three experiments. The steers of the first and second experiments are described in Bulletin No. 385 (*4*) of the Texas station (see especially Table 1) as the 1924, 1925, 1926, and SMS steers. The steers of the third experiment were similar in breeding to those described in Bulletin 385 as 1924, 1925, and 1926 steers, but were born and fed at later dates. The steers of the fourth and fifth experiments were fed under the direction of J. H. Knox in a test involving a comparison of various market grades of feeder steers. All steers were given good rations and all made good gains, only one lot failing to gain at least 2 pounds per head per day.

METHODS OF CALCULATION

Correlation coefficients were calculated by the usual product-moment method for each lot of pigs or steers separately, observed gain, initial weight, and each estimate of gain being used as the variables. All possible correlations between these variables were calculated, thus making from as few as 3 correlation coefficients for each lot in the first steer experiment, where only 1 man took part, to as many as 78 correlation coefficients for each lot in the fourth steer experiment, where 11 men took part. The calculations for each lot were made separately in order not to include in the coefficients any effects of differences in rations or in breeding of the different lots. Since the numbers in each lot were small, the observed coefficients tended to be distinctly biased in the direction of largeness whether plus or minus. A correction for this was made according to the method suggested by Fisher *(2, p. 171–172)* whereby the quantity $\frac{r}{2(n-1)}$ is subtracted from the Z value corresponding to the observed r. The correlation coefficients for the same two variables for all the different lots in the same experiment were averaged together according to Fisher's method to obtain an average correlation coefficient for the different lots in each experiment. The calculation of this average is illustrated in Table 1.

TABLE 1.—*Illustration of method used in averaging correlation coefficients*

[Correlation between initial weight and gain, third steer experiment]

Designation of lot	Number of steers in lot	Degrees of freedom[a] in Z	Observed r	Corresponding Z value	Correction for bias of small numbers	Corrected Z value	Corrected Z value multiplied by degrees of freedom
1927 Herefords	4	1	+0.929	+1.6510	+0.1548	1.4962	1.4962
1927 Brahmans	13	10	+.570	+.6475	+.0238	.6237	6.2370
1927 Back crosses	9	6	+.455	+.4910	+.0284	.4626	2.7756
1928 Herefords	6	3	−.092	−.0923	−.0092	−.0831	−.2493
1928 Brahmans	11	8	+.123	+.1236	+.0062	.1174	.9392
1928 Back crosses	14	11	+.323	+.3350	+.0124	.3226	3.5486
Total	57	39					14.7473

Average Z=0.3781. Corresponding average r=+0.361.

[a] "Degrees of freedom" is a technical statistical term used to designate the number of items really free to vary in the data from which the statistic in question was calculated. In general the number of degrees of freedom is only slightly less than the total number of items but may be very distinctly less for averages based upon a large number of subgroups each calculated separately, as was the case in this study.

This method of averaging seems to the writer better suited to these data than any other method yet suggested. It is not entirely adequate to the problem of averaging all the intercorrelations of several variables, but adequate methods for that have not yet been developed. A suggestion of the extent of error in the methods employed may be gained from the fact that, when these average r's are used, the squared multiple correlations between final weight as the dependent variable and initial weight and gain as the independent variables (which, of course, should equal 1.000, all primary correlations being carried to the third place) are found to be as follows:

First pig experiment	0.950
Second pig experiment	.989
Third pig experiment	.999
First steer experiment	.978
Second steer experiment	1.006
Third steer experiment	1.036
Fourth steer experiment	1.060

These discrepancies are slight but may be large enough to cast some doubt upon the reality of small differences which the further analysis of these average correlations might seem to show. Consequently, the correlation coefficients are also given as actually calculated without correction for bias due to small numbers. Where this would be too cumbersome and space-consuming the distributions of the correlation coefficients are presented.

RESULTS

FIRST EXPERIMENT WITH PIGS

In the first experiment there were five lots of eight pigs each, which were fed for 70 days and made an average daily gain of 1.55 pounds from an average initial weight of 80 pounds. The average intralot standard deviation (35 degrees of freedom) of daily gains was 0.207, thus giving a coefficient of variability of 13.3 per cent. The three men who acted as a committee freely discussed each pig and agreed upon a single set of estimates. This procedure did not seem entirely satisfactory to any of the men and in all later experiments each man

worked independently. The results are shown in Table 2. The symbols are: G=gain, J=judgment or estimate of gain, I=initial weight.

TABLE 2.—*Correlation coefficients from first feeding experiment with pigs*

Symbol [a]	Correlation coefficients for pigs in—					Average by Fisher's method
	Lot 1	Lot 2	Lot 3	Lot 4	Lot 5	
r_{GJ}	+0.16	−0.18	−0.28	+0.53	−0.03	+0.05
r_{GI}	+.01	−.31	−.32	+.50	−.18	−.05
r_{JI}	+.96	+.95	+.96	+.98	+.92	+.95
$r_{GJ \cdot I}$	+.52	+.38	+.11	+.26	+.34	+.32
$r_{GI \cdot J}$	−.50	−.45	−.20	−.16	−.38	−.32
$R_{G \cdot IJ}$						.33

[a] See text for explanation.

Here r_{JI} is uniformly high and r_{GJ} is slightly larger when positive and smaller when negative than r_{GI}. This seems to mean that the men in making their estimates were influenced greatly (far more than they suspected) by the differences in initial size of the pigs. In this experiment (unlike most of the later ones) r_{GI} tends to be slightly negative and, because of the very strong association of I and J, r_{GJ} is brought down to values nearly as low as r_{GI}. This is shown also by the partial correlation coefficients, among which those between gain and judgment, initial weight being constant, are uniformly positive and are of considerable size, while those between gain and initial weight, judgment being constant, are as uniformly negative and are also of considerable size. Thus it appears that in this experiment the things associated with initial weight but regarded as unimportant by the judges were negatively correlated with gains. On the other hand, the things which the judges considered but which were not reflected in initial weight were positively associated with gain. So closely were judgment and initial weight associated that the primary correlation coefficients between either of them and gain are not far from zero. Balancing the lots according to initial weight alone or according to judgment alone would have had practically no effect on the standard deviation of gains. And yet if the pigs had been exactly alike both in initial weight and in the opinion of the judges, the variation in the gains would have been about 5 per cent less than it actually was.

SECOND EXPERIMENT WITH PIGS

Six lots of 10 pigs each were fed for 70 days and made an average daily gain per head of 1.73 pounds from an average initial weight of 90 pounds. The average intralot standard deviation (54 degrees of freedom) of the individual daily gains was 0.169 pound, thus giving an apparent coefficient of variability of 9.8 per cent—a quite uniform group of gains. Three men participated in this experiment, each making his estimates without consulting the others although all were made at the same hour, a day or two after the pigs had been divided into lots for experimental purposes. The results are shown in Table 3. The symbols A, B, and C represent the estimates made by the three men and I and G represent initial weight and gain, as before.

TABLE 3.—*Correlation coefficients from second feeding experiment with pigs*

Symbol*	Correlation coefficient for pigs in—						Average by Fisher's method
	Lot 1	Lot 2	Lot 3	Lot 4	Lot 5	Lot 6	
r_{GA}	0.79	0.67	0.48	0.88	0.53	0.43	0.65
r_{GB}	.90	.68	.66	.73	.21	.73	.68
r_{GC}	.58	.69	.33	.78	.44	.47	.55
r_{GI}	.89	.70	.35	.68	.40	.58	.62
r_{IA}	.83	.90	.94	.85	.92	.57	.85
r_{IB}	.90	.90	.80	.94	.86	.81	.87
r_{IC}	.52	.81	.86	.88	.94	.92	.85
r_{AB}	.76	.88	.94	.88	.85	.52	.83
r_{AC}	.69	.97	.89	.87	.97	.59	.88
r_{BC}	.69	.81	.83	.91	.85	.70	.80

* See text for explanation.

In this experiment all correlations are positive and nearly all are large. The correlations between judgments and initial weight are prevailingly high. The different men agreed quite closely with each other. The correlations between judgments and gain are distinctly lower than those between the different judgments or between the judgments and initial weight. Initial weight and gain are correlated almost as closely as the judgments and gain are. The partials between initial weight and gain, one judgment being constant, and the partials between each judgment and gain, initial weight being constant, are much lower than the corresponding primary coefficients. This shows that much of the success which the men had in estimating the gains of the individual pigs came from the attention which they paid to things already largely reflected in initial weight.

The multiple correlation coefficient between gain as the dependent variable and initial weight and the three judgments as the independent variables is 0.707, which indicates that about half (R^2) of all the causes of variation in the gains in this experiment were seen by one or more of the judges or were reflected in initial weight.

The multiple correlation coefficient is large enough to be of undoubted statistical significance, but when any one of the four independents is made constant the resulting partials become so small as to raise the question whether the evidence is sufficient to prove their reality. There seems to be no escape from the conclusion that each of the independent variables was positively associated with gain, but that most of this association was shared jointly by all four independent variables. The differences between judges are far below the level of statistical significance.

THIRD EXPERIMENT WITH PIGS

At the beginning of this experiment there were 9 lots of pigs each containing 10 animals, but 5 of the pigs became unthrifty and were removed before the end of the experiment. Consequently 5 lots of 10 pigs each, 3 lots of 9 pigs each, and 1 lot of 8 pigs finished the experiment. The pigs were fed for 100 days, and made an average daily gain of 1.60 pounds from an average initial weight of 51 pounds. The standard deviation of the average daily gains of the individual pigs within each lot (76 degrees of freedom) was 0.194 pound, thus giving a coefficient of variation of 12.1 per cent—a more uniform

group of gains than the 17 per cent average found by Mitchell and Grindley (*8*).

Four men participated in this experiment, but there was much confusion in the pens because of an unfamiliar method of identifying the pigs. Not being entirely satisfied that they had done their best, three of the men went back three days later when the pigs were adequately marked and again estimated the individual gains without referring to their previous estimates. The judges felt more confidence in their second set of estimates, although it may be remarked parenthetically that the data when analyzed did not justify much greater confidence.

TABLE 4.—*Correlation coefficients from third feeding experiment with pigs*

Symbols *	Correlation coefficients, for pigs in—									Average by Fisher's method
	Lot 1, 9 pigs	Lot 2, 10 pigs	Lot 3, 10 pigs	Lot 4, 8 pigs	Lot 5, 10 pigs	Lot 6, 9 pigs	Lot 7, 9 pigs	Lot 8, 10 pigs	Lot 9, 10 pigs	
rA_1G	0.87	0.40	0.61	0.72	0.49	0.43	0.73	0.84	0.11	0.59
rB_1G	.81	.53	.53	.81	.64	.57	.67	.88	.28	.64
rC_1G	.69	.31	.51	.79	.60	.56	.65	.86	.28	.59
rDG	.80	.42	.71	.68	.43	.78	.73	.77	.37	.63
rA_2G	.85	.33	.53	.87	.50	.60	.84	.87	.47	.67
rB_2G	.78	.40	.51	.83	.42	.69	.72	.89	.42	.64
rC_2G	.91	.37	.65	.86	.54	.46	.73	.92	.39	.68
rIG	.86	.35	.60	.86	.36	.65	.70	.83	.24	.62
rA_1I	.91	.84	.89	.89	.81	.78	.93	.93	.88	.87
rB_1I	.84	.93	.94	.77	.84	.84	.83	.80	.95	.87
rC_1I	.73	.85	.96	.80	.86	.96	.97	.99	.96	.93
rDI	.79	.83	.85	.92	.88	.87	.92	.91	.98	.89
rA_2I	.91	.98	.98	.93	.92	.92	.89	.93	.95	.94
rB_2I	.87	.96	.95	.84	.85	.88	.96	.91	.92	.91
rC_2I	.94	.98	.97	.94	.91	.86	.96	.93	.97	.94
rA_1A_2	.94	.84	.85	.67	.91	.71	.91	.96	.85	.87
rB_1B_2	.94	.98	.95	.79	.83	.87	.88	.97	.88	.91
rC_1C_2	.78	.90	.92	.81	.91	.91	.96	.91	.94	.90

* See text for explanation.

Both the first and second sets of estimates were used in the calculations, thus making eight independent variables (the seven judgments and initial weight) and one dependent variable (gain). The results are shown in Table 4. The letters *A*, *B*, *C*, and *D* represent the judgments, the subscript numerals indicating whether the first or the second set of estimates is meant. *I* and *G* indicate initial weight and gain, respectively. The averages by Fisher's method are each based upon 58 degrees of freedom, i.e., they are statistically equivalent to a simple correlation calculated upon a population of 61.

Besides the correlations shown, there were 162 other correlations between the estimates of one judge and those of the other judges. The distribution of these was as follows:

Size of coefficient	Number of coefficients found	Size of coefficient	Number of coefficients found
0.45–0.50	2	0.75–0.80	10
0.50–0.55	1	0.80–0.85	21
0.55–0.60	4	0.85–0.90	37
0.60–0.65	3	0.90–0.95	46
0.65–0.70	2	0.95–1.00	27
0.70–0.75	9		

The average of all these 162 coefficients according to Fisher's method was +0.885.

The correlation coefficients calculated in this experiment may be divided into four groups: (1) Those involving gain, (2) those between initial weight and the seven judgments, (3) those between the first and second judgments of the same men, and (4) those between the judgment of one man and the judgments of the other three. It is evident merely from inspection (and consideration of the averages confirms this) that the correlations of the last three groups were of practically the same magnitude, while those involving gain were distinctly smaller, although still large enough to be of undoubted statistical significance. All of the 324 simple correlation coefficients were positive and only one fell below +0.24.

The fact that the correlations between a man's first judgment and his second judgment were no larger than the correlations between his judgment and the other men's judgments points either to a very considerable degree of uncertainty in his mind when he made the estimates or to very considerable changes in the appearance of the pigs in the three days that intervened between first and second estimates, probably the former.

As in the second experiment, when initial weight is made constant much of the correlation between judgment and gain disappears. It is likewise true that if any one of the seven judgments is made constant much of the correlation between initial weight and gain disappears. In other words, the men were paying attention to things which actually were associated with the gaining ability of the pigs but which were already in large part reflected in differences in initial weight. The multiple correlation coefficient between all eight independent variables and gain was 0.702, thus indicating that almost half (R^2) of the causes of differences in gains were foreseen by at least one judge, or were associated with differences in initial weight. When initial weight is left out of consideration the coefficient of multiple correlation falls only from 0.702 to 0.698. This is to be interpreted as showing that practically all of the association between initial weight and gain rested on things also seen by one or more of the men. Likewise if the three estimates which were made on the second occasion are omitted altogether, the multiple correlation coefficient with gain falls only from 0.702 to 0.664. This seems to mean that while the second day's estimates actually were a bit more accurate than the first, yet nearly everything of importance which the men saw on the second occasion was also seen by them on the first occasion.

Whether there were any real differences in the ability of the different judges to predict gains remains doubtful. The differences in some of the first-order partial correlation coefficients seem large enough to border on statistical significance and yet certain facts are opposed to this interpretation. For example, the greatest difference found when initial weight was made constant was not a difference between the estimates of two judges but a difference between the two estimates of one judge. As a group the judges seem rather certainly to have seen a few things which were associated with gain but which were not reflected in initial weight, but the total importance of these things is small compared with that of the things seen by the judges and also reflected in initial weight.

FIRST EXPERIMENT WITH STEERS

Six lots of steers were fed for 112 days and made an average daily gain of 2.56 pounds, with an average intralot standard deviation (52 degrees of freedom) of 0.271 pounds in the individual average daily gains. The coefficient of variation was 10.6 per cent, which is distinctly less than the average found by Mitchell and Grindley (*8*). Three of the lots were calves about 8 to 9 months old when feeding began and the other three were one year older. All had been bred and raised at the Texas station. They are described in more detail in Texas Agricultural Experiment Station bulletins 385 (*4*) and 409 (*6*) under the designation 1924 and 1925 calves. The results of the experiment are shown in Table 5. *J* represents the estimates; *I*, initial weight; and *G*, gain. The averages shown in the last column are each based upon 40 degrees of freedom—i. e., they are statistically equal to simple correlations calculated upon a group of 43 steers. On populations of this size correlations need to be larger than 0.30 before the probability of their being accidental variations will fall below 0.05, and larger than 0.39 before that probability will fall below 0.01. The estimates were much influenced by factors associated with large initial weight. The other parts of the ideal which the judge applied to these steers were neutral or slightly wrong. The multiple correlation between gain as the dependent variable and initial weight and estimated gain was 0.297, thus indicating that less than 9 per cent (R^2) of the causes of the variations in gain in this experiment were either correlated with initial weight or were foreseen by the man in charge.

TABLE 5.—*Correlation coefficients from first feeding experiment with steers*

Symbol [a]	Correlation coefficients for—						Average by Fisher's method
	Steers born in 1924			Steers born in 1925			
	Herefords, 10 head	First-cross Brahmans, 14 head	Back crosses 4 head	Herefords, 10 head	First-cross Brahmans, 14 head	Back crosses 4 head	
r_{JG}	−0.36	+0.05	−0.58	+0.45	−0.36	+0.68	−0.03
d_G	+.05	−.10	+.69	+.58	+.18	+.47	+.19
r_{IJ}	+.66	+.80	−.32	+.88	+.46	+.86	+.70

[a] See text for explanation.

SECOND EXPERIMENT WITH STEERS

Six lots of steers were fed for 111 days in the winter of 1926–27. They are the last six lots of steers described in Texas Agricultural Experiment Station Bulletin 385 (*4*). One 1926 back-cross steer used in that study was omitted from this one, because, the slaughter data on him were incomplete and he could not be used in the estimates of final value. The gains were reasonably good, averaging 2.05 pounds per head per day for the entire group of 63 steers. The average intralot standard deviation (57 degrees of freedom) of the individual average daily gains was 0.223 pound, thus giving a coefficient of variation of 12.0 per cent, which is distinctly less than the average of about 17

per cent found by Mitchell and Grindley (*8*). Four men took part in the estimates in this experiment. Not only were the gains estimated as in the other experiments but a new feature was added by each man estimating independently what the individual steers would be worth per pound at the close of the experiment. Each judge studied the lot until he was sure that he had a good idea of the differences between the steers. He then rated the future worth of each steer as a certain percentage more or less than the average worth of that lot. (In later experiments it was found more satisfactory to rate the best steer at 100 and to work down from that figure.) The dressed carcasses were appraised by three or more meat salesmen who were unacquainted with the breeding, feeding, or previous history of the individual animals. This average appraised price for the dressed meat from each steer was multiplied by the dressed weight of that carcass and was then divided by the live weight of the steer at the close of the feeding experiment.

Thus there were taken into account both the market desirability of the meat and the differences in yield. The figure thus obtained for the final value of each steer is of course not absolutely accurate [7] but it seemed the most accurate and least subjective standard available.

The results of this experiment are shown in Table 6. *A*, *B*, *C*, and *D* represent the estimates of gains, while *a*, *b*, *c*, and *d* represent the estimates of the corresponding men on market desirability of the finished steers. *I* is initial weight, *G* is gain, *P* is appraised price per pound of the dressed meat, and *V* is the value of the meat per pound of live weight.

The averages obtained by Fisher's method rest on 45 degrees of freedom; that is, they are based on as large a population as simple correlations calculated upon groups of 48. They need to be larger than 0.28 before the probability of their being chance variations will fall below 0.05 and they should be larger than 0.37 before that probability will fall below 0.01. Thus the correlations involving *G* are probably significant even when considered singly, and certainly so when it is noted that all five are of the same sign and of about the same magnitude. Correlations involving *P* are a little larger than those involving *G*, and those involving *V* are slightly larger than those involving *P*, although neither of these sets of differences is large enough or consistent enough to be unmistakably significant.

Again, as in the second and third pig experiments, there is a high correlation between the different estimates of gain, and a high correlation between initial weight and the estimates of gain. The multiple correlation of *G* as dependent variable with the four judgments and initial weight as independent variables is 0.428, and when initial weight is omitted this figure falls only to 0.421. Eighteen per cent of the causes of variation in the gains of these steers were foreseen by the four men or were reflected in initial weight. While this is perhaps a significant accomplishment on the part of the judges, yet the 82 per cent of the causes of variation unseen by them and not reflected in initial weight shows by vivid contrast the small extent to which the problem of estimating gains was solved.

[7] Its accuracy has been studied in some detail and the conclusions published by Lush, Black and Semple (*5*).

TABLE 6.—*Correlation coefficients from second feeding experiment with steers*

Symbol *	Correlation coefficient for—						Average by Fisher's method
	Steers born in 1926			S. M. S. steers			
	Herefords, 13 head	First-cross Brahmans, 17 head	Back crosses, 4 head	Fed ground milo heads and whole bundles, 10 head	Fed ground milo heads and chopped bundles, 10 head	Fed whole milo heads and whole bundles, 9 head	
rAG	+0.52	+0.47	−0.70	+0.57	−0.08	+0.46	+0.30
rBG	+.55	+.51	−.72	+.21	−.29	+.43	+.32
rCG	+.34	+.43	−.32	+.44	−.12	+.09	+.27
rDG	+.24	+.46	−.34	+.29	−.15	+.72	+.32
rIG	+.60	+.49	+.18	+.34	−.40	+.52	+.36
rAI	+.94	+.96	+.56	+.81	+.30	+.91	+.88
rBI	+.90	+.95	+.42	+.10	−.14	+.55	+.74
rCI	+.85	+.98	+.80	+.90	+.78	+.64	+.90
rDI	+.79	+.81	+.17	+.86	+.90	+.92	+.83
rAB	+.87	+.92	+.95	+.20	+.18	+.35	+.72
rAC	+.82	+.96	+.80	+.88	+.34	+.66	+.84
rAD	+.69	+.74	+.52	+.78	+.49	+.93	+.73
rBC	+.83	+.93	+.58	+.33	−.55	+.17	+.64
rBD	+.65	+.81	+.75	+.09	−.28	+.46	+.51
rCD	+.72	+.80	−.01	+.85	+.82	+.52	+.74
raP	+.38	+.63	+.83	+.71	+.07	+.45	+.49
rbP	+.37	+.43	+.93	+.27	−.03	+.15	+.30
rcP	+.56	+.16	+.96	+.42	+.61	+.16	+.39
rdP	+.51	+.40	−.52	+.29	+.19	+.46	+.36
rIP	+.45	+.54	+.66	+.42	+.10	+.38	+.41
raV	+.46	+.68	+.93	+.56	+.04	+.33	+.48
rbV	+.47	+.46	+.71	+.36	−.00	+.22	+.34
rcV	+.56	+.25	+.72	+.19	+.66	+.44	+.41
rdV	+.66	+.34	−.45	+.43	+.45	+.42	+.43
rIV	+.57	+.61	+.92	+.52	+.29	+.47	+.52
raI	+.67	+.80	+.91	+.17	+.56	+.16	+.59
rbI	+.78	+.73	+.39	−.28	+.34	+.00	+.48
rcI	+.67	+.72	+.41	−.25	+.59	−.20	+.46
rdI	+.71	+.78	−.44	+.65	+.80	+.78	+.72
rab	+.78	+.74	+.57	+.62	+.75	+.74	+.72
rac	+.74	+.43	+.65	+.51	+.38	+.72	+.55
rad	+.49	+.73	−.74	+.44	+.50	+.57	+.54
rbc	+.75	+.50	+.98	+.45	+.44	+.57	+.57
rbd	+.54	+.74	−.29	+.25	+.33	+.28	+.49
rcd	+.50	+.29	−.45	+.04	+.63	+.13	+.32

* See text for explanation.

Much of what was seen by each man was seen by the others and was also reflected in initial weight. This is shown by the small size of the partial correlation coefficients when initial weight or one of the judgments is made constant. The coefficient of multiple correlation between V as the dependent variable and a, b, c, and d as independent variables is 0.559, indicating that 31 per cent of the causes of the differences in final value were foreseen by one or more of the four men.

The fact that the estimates of V (value of meat per pound of live weight) are slightly more accurate than the estimates of P (appraised price of dressed meat) seems to indicate that vagaries of dressing percentage were not the cause of failure to estimate V more closely. V is merely P multiplied by individual dressing percentage. The data indicate (although with doubtful statistical significance) that the men had some success in estimating even so far in advance which steers would be paunchy and "wasty"—a point upon which they had many misgivings when making the estimates.

The men paid less attention to initial weight when they were estimating final values than when they were estimating gains. Also, they agreed with each other less closely when estimating final value than when estimating gain.

THIRD EXPERIMENT WITH STEERS

Six lots of steers totaling 57 head were fed for 114 days in the winter of 1928–29. They were of Hereford and mixed Hereford and Brahman breeding, bred and raised under the same conditions as those described in Texas Bulletins Nos. 385 and 409. In these lots were included all steers born at the Ranch Experiment Station in 1927 and 1928. The 1927 steers were approximately 19 to 22 months old when the formal feeding period began, while the 1928 steers were about 7 to 10 months old. The average daily gain per head for all lots was 2.53 pounds, with an average intralot standard deviation (51 degrees of freedom) of 0.398 pound, thus giving a coefficient of variability of 15.8 per cent, which is larger than was found in the other experiments, although still below the average of 17 per cent reported by Mitchell and Grindley (*8*).

Only two men took part in this experiment. Estimates of value per pound of live weight when finished were also made. The results are shown in Table 7. A and B denote the estimates of gain; a and b, the estimates of value per pound of live weight when finished; I, initial weight; G, gain; P, appraised value of dressed meat; and V, meat value of finished steer per pound of live weight.

TABLE 7.—*Correlation coefficients from third feeding experiment with steers*

Symbol [a]	Correlation coefficients for —						
	Steers born in 1927			Steers born in 1928			Average by Fisher's method
	Herefords, 4 head	First-cross Brahmans, 13 head	Back crosses, 9 head	Herefords, 6 head	First-cross Brahmans, 11 head	Back crosses, 14 head	
r_{AG}	+0.28	+0.53	+0.53	+0.36	+0.22	−0.01	+0.30
r_{BG}	+.64	+.63	+.59	+.48	+.20	+.03	+.36
r_{IG}	+.93	+.57	+.46	−.09	+.12	+.32	+.36
r_{AI}	+.19	+.86	+.61	+.86	+.92	+.29	+.72
r_{BI}	+.80	+.55	+.59	+.79	+.84	+.46	+.62
r_{AB}	−.42	+.59	+.34	+.93	+.73	−.22	+.42
r_{aP}	−.45	+.48	−.36	−.67	+.37	+.66	+.29
r_{bP}	+.89	+.13	−.51	−.26	+.38	+.28	+.12
r_{IP}	+.35	+.76	−.74	+.10	+.44	−.06	+.20
r_{aV}	−.65	+.40	−.44	+.23	+.71	+.59	+.37
r_{bV}	+.76	+.15	−.26	+.39	+.68	+.18	+.26
r_{IV}	+.48	+.74	−.44	+.82	+.76	−.12	+.40
r_{aI}	−.80	+.33	+.46	+.62	+.68	+.12	+.36
r_{bI}	−.04	+.44	+.82	+.80	+.79	+.12	+.55
r_{ab}	−.00	+.13	+.10	+.65	+.66	+.14	+.29

[a] See text for explanation.

The averages in the last column are each based on 39 degrees of freedom; that is, they are as reliable as simple correlations calculated upon a group of 42 steers. The results are similar to those from the previous experiments except that the agreement between the men

was less in this instance. The correlations with gain are distinctly less than those between judgment and initial weight. The correlations with gain are on the border line of statistical significance when considered singly, but must be regarded as significant since all three are of the same sign and about the same magnitude.

The multiple correlation between gain as the dependent variable and A, B, and I as independent variables is 0.407, and this falls only to 0.397 when initial weight is left out of consideration. A little more than 16 per cent of the things which caused the differences in gains were seen by one or both men or were associated with differences in initial weight. The first-order partial correlation coefficients indicate again, as in the previous experiments, that much of what was seen by one man was also seen by the other or was reflected in intital weight.

Both men had some success in estimating the final value of the steers, one being more and the other less successful with value than with gain. Both had more success in estimating V than they would have had if the only causal connection had been through P; that is, they apparently took future dressing percentage into consideration with some slight degree of success.

The multiple correlation between V as the dependent variable and the two judgments and initial weight as independent variables was 0.472. The things which one or both men saw or which were associated with initial weight determined about 22 per cent of the differences in final value per pound of live weight but less than 10 per cent of the differences in appraised value of the dressed meat. When intital weight is left entirely out of consideration the men together saw 16 per cent of the causes of differences in final value per pound of live weight and nearly 9 per cent of the causes of differences in the appraised prices of the dressed meat.

FOURTH EXPERIMENT WITH STEERS

Forty steers were fed for 150 days at College Station during the winter of 1928–29. They were used in a study of market grades and were purchased on the Fort Worth market, 10 head to represent each of the feeder grades—Choice, Good, Medium, and Common. Their previous history was only slightly known, but at the beginning of the experiment they appeared to be about 10 to 15 months old and their average weight was 523 pounds. The average daily gain per head for the entire group was 2.35 pounds. The corresponding average intralot standard deviation (36 degrees of freedom) was 0.287 pound, thus giving a coefficient of variation of 12.2 per cent. The gains of these steers were more uniform than the average found by Mitchell and Grindley (*8*).

Eleven men estimated independently the gains for each lot. No attempt was made to estimate final values. The results are shown in Table 8. I indicates initial weight and G indicates gain. The other letters indicate the estimates of the various men. All further calculations are based upon the average correlations in the last column of the table.

TABLE 8.—*Correlation coefficients from fourth feeding experiment with steers*

Symbols [a]	Correlation coefficients for—				Averages by Fisher's method
	Choice feeder steers	Good feeder steers	Medium feeder steers	Common feeder steers	
r_{GA}	−0.07	+0.35	−0.04	+0.31	+0.10
r_{GB}	−.35	+.30	−.41	−.02	−.12
r_{GC}	−.22	+.40	−.02	−.13	+.01
r_{GD}	−.54	+.54	−.55	+.14	−.11
r_{GE}	−.44	+.16	−.44	−.07	−.20
r_{GF}	−.26	+.61	−.17	+.40	+.16
r_{GH}	−.49	+.88	−.49	+.34	+.16
r_{GJ}	−.38	+.55	+.35	+.49	+.26
r_{GK}	−.63	+.50	−.34	+.66	+.06
r_{GL}	−.26	+.44	−.50	+.38	+.01
r_{GM}	−.29	+.70	−.36	+.19	+.09
r_{GI}	−.62	+.67	−.34	+.09	−.04
r_{IA}	+.69	+.17	+.24	+.56	+.34
r_{IB}	+.63	+.48	+.47	+.77	+.58
r_{IC}	+.16	+.76	+.87	+.21	+.57
r_{ID}	+.80	+.89	+.64	+.64	+.75
r_{IE}	+.69	+.69	+.52	+.47	+.58
r_{IF}	+.56	+.85	+.61	+.74	+.69
r_{IH}	+.86	+.77	+.59	+.28	+.66
r_{IJ}	+.85	+.39	−.12	+.73	+.53
r_{IK}	+.85	+.81	+.67	+.48	+.71
r_{IL}	+.71	+.68	+.67	+.61	+.65
r_{IM}	+.52	+.80	+.57	+.29	+.55

[a] See text for explanation.

The average correlation between initial weight and the 11 sets of estimates is +0.629, whereas the average correlation between gain and the 11 sets of estimates is +0.039. The average correlation between one judge's estimates and the estimates of the other judges is +0.491. The same steers were used again and again in the correlations entering into these three averages. A glance at Table 8 shows that all correlations involving gain were negative—many of them strongly so—for the choice steers, all were positive for the good steers, all but one were negative for the medium steers, etc. The tendency here shown for all judges to do well with one lot and poorly with another was present to a lesser degree in the earlier experiments. If there happened to be some exceptional steers in the Choice lot or in the Good lot, the mere multiplication of judges who evidently have much the same ideal in mind would not add much to the general applicability of the figures. The number of steers needs also to be increased. Doubtless the averages are more reliable than those in the last column of Table 8, but less reliable than if an equal number of judges had worked on a much larger number of steers, and each steer had been used for the estimates by only two men. The distribution of the 220 original uncorrected correlation coefficients between the estimates of each man and those of every other man for each lot of 10 steers was as follows:

−0.50 to −0.59	1	+0.20 to +0.29	13
−0.40 to −0.49	1	+0.30 to +0.39	28
−0.30 to −0.39	1	+0.40 to +0.49	22
−0.20 to −0.29	9	+0.50 to +0.59	31
−0.10 to −0.19	4	+0.60 to +0.69	33
−0.00 to −0.09	4	+0.70 to +0.79	30
+0.00 to +0.09	5	+0.80 to +0.89	19
+0.10 to +0.19	14	+0.90 to +0.99	5

The averages in the last column of Table 9 need to be larger than 0.35 if the probability of their being accidental is to fall below 0.05. On that basis, not one of the correlations with gain is significant, but practically all of the correlations between initial weight and the estimates are significant, and so also are nearly all the correlations between 1 man's estimates and the estimates of the other 10 men. This is quite in accord with the previous experiments except that here the correlations with gain average close to zero.

When the average correlations in the last column of Table 8 are used, with gain as the dependent variable and initial weight and the 11 judgments as the independent variables, the multiple correlation coefficient is +0.736, but this sums up everything associated with gain, positively or negatively, and whether seen by only 1 man or by all 11. It should almost inevitably be rather large even if no one man by himself was reasonably successful in his estimates. A circumstance which may have had an important bearing on the outcome of this experiment was that the steers used were selected on the public market for their conformity to the standard market grades of feeder steers. They may not have been raised on the same ranch or even in the same region. Because they were selected for their conformity to the standard market grades, the steers within each lot were doubtless more uniform in outward appearance than those in the other experiments but less uniform in previous treatment. That this greater uniformity in outward appearance did not result in much, if any, greater uniformity of gains may be seen by comparing the coefficient of variability of their gains (12.2 per cent) with those in the first three experiments (10.6, 12, and 15.8 per cent). All but three lots of the steers in the first three experiments were bred and raised at the Texas station on one 5-section ranch and were subjected to the same treatment in feeding practices and in handling.

FIFTH EXPERIMENT WITH STEERS

Feeding of 40 steers was begun at College Station late in September, 1929, to repeat the preceding year's experiment. One died of anthrax during the experiment. The steers were purchased on the Fort Worth market, 10 head to represent each of the feeder grades—Choice, Good, Medium, and Common. Their previous history was unknown, but they appeared to be about 10 to 15 months old and averaged 535 pounds at the beginning of the experiment. The average daily gain per head for the entire group of 39 for 157 days was 2.21 pounds. The corresponding average intralot standard deviation (35 degrees of freedom) was 0.330 pound, thus giving a coefficient of variation of 14.9 per cent. The gains made by these steers were slightly more uniform than the average found by Mitchell and Grindley (*8*).

Ten men on the college, station, and extension staffs estimated independently the gain for each lot, and they estimated also what the steers would be worth per pound on foot at the end of the feeding period. A group of 10 senior students in animal husbandry who were trying out for the judging team used these steers for judging practice just before the beginning of the feeding period and made estimates in the same manner as the staff members. The results of the faculty estimates are shown in Tables 9 and 11 and those of the

students in Tables 10 and 12. *G* indicates gain; *I* initial weight; and *V*, final value per pound of live weight. These final values are thought to be slightly less accurate than those in the second and third steer experiments because these were based upon a single appraisal rather than on the average of three independent appraisals of the dressed meat.

TABLE 9.—*Correlation coefficients from fifth feeding experiment with steers*

[Staff members' estimates of gain]

Symbol *	Correlation coefficient for—				
	Choice feeder steers	Good feeder steers	Medium feeder steers	Common feeder steers	Averages by Fisher's method
r_{GA}	+0.40	+0.26	+0.45	+0.32	+0.34
r_{GB}	+.71	+.04	−.04	−.32	+.29
r_{GC}	+.34	+.14	+.08	+.24	+.19
r_{GD}	+.46	+.04	+.38	+.39	+.30
r_{GE}	+.55	−.45	+.46	−.16	+.09
r_{GF}	+.59	+.26	+.17	+.43	+.35
r_{GH}	+.54	+.08	+.18	−.20	+.14
r_{GJ}	−.19	−.27	+.61	+.82	+.34
r_{GK}	+.29	+.14	+.37	+.10	+.21
r_{GL}	+.23	−.28	+.55	−.13	+.10
r_{GI}	+.41	+.15	+.17	−.17	+.13
r_{IA}	+.88	+.36	+.34	+.68	+.59
r_{IB}	+.84	+.46	+.75	+.42	+.63
r_{IC}	+.79	+.68	+.57	+.67	+.66
r_{ID}	+.85	+.72	+.87	+.79	+.80
r_{IE}	+.66	+.58	+.75	+.48	+.60
r_{IF}	+.63	+.82	+.74	+.54	+.68
r_{IH}	+.88	+.77	+.85	+.44	+.75
r_{IJ}	+.52	+.64	+.27	−.11	+.34
r_{IK}	+.85	+.76	+.87	+.87	+.83
r_{IL}	+.84	+.64	+.85	+.96	+.85

* See text for explanation.

Each correlation shown in the last column of Tables 9 to 12 is based on 27 degrees of freedom. The average of the 10 average correlations between initial weight and estimates is +0.694, whereas the average of the correlations between gain and the estimates is +0.237. The average correlation between one man's estimate and the estimates of the other men is +0.583. The distribution of the 180 original uncorrected correlation coefficients between the estimates of each man and those of every other man for each lot of steers was as follows:

−0.30 to −0.39	2	+0.30 to +0.39	15
−0.20 to −0.29	2	+0.40 to +0.49	18
−0.10 to −0.19	1	+0.50 to +0.59	22
−0.00 to −0.09	2	+0.60 to +0.69	35
+0.00 to +0.09	2	+0.70 to +0.79	33
+0.10 to +0.19	8	+0.80 to +0.89	23
+0.20 to +0.29	11	+0.90 to +0.99	6

The averages in the last column of Table 10 need to be larger than +0.35 if the probability of their being accidental is to be regarded as less than 0.05. Only three of the average correlations between gain and estimate come close to that level of significance. However, all 10 of those correlations are positive and the average of 0.237 between the actual gains and all estimates seems to prove that the positive

correlation between estimate and actual gain was real even though small.

The much higher correlations found between estimates of gain and initial weight than between estimates of gain and actual gain are in harmony with the results of previous experiments. The partial correlations between estimate and gain are only slightly smaller than the corresponding primary correlation coefficients. The partial correlations between initial weight and gain, the various judgments being constant, are distinctly smaller than the corresponding primary coefficients. These findings indicate that differences in initial weight rested on many things, only a few of which were associated with gain. Those few which were associated with gain were also seen by the men. The men saw in addition a small number of other things not associated with initial weight but associated with gain, and they also laid emphasis on many things associated with initial weight which were not actually associated with gain. Hence the high correlation between estimate and initial weight.

The multiple correlation coefficient between gain as the dependent variable and the 10 estimates and initial weight as the independent variables was 0.628. That the net contribution of initial weight to the forecasting of gains is practically zero in this case is indicated by the fact that the multiple correlation coefficient when initial weight is omitted falls from 0.628 only to 0.624.

The primary uncorrected correlation coefficients between the estimates of the 10 students and gain and initial weight are shown in Table 10, together with averages for all four lots calculated by Fisher's method.

TABLE 10.—*Correlation coefficients from fifth feeding experiment with steers*

(Student estimates of gain)

Symbol [a]	Correlation coefficients for—				Averages by Fisher's method
	Choice feeder steers	Good feeder steers	Medium feeder steers	Common feeder steers	
r_{GM}	+0.29	−0.28	+0.56	−0.14	+0.11
r_{GN}	+.22	−.25	+.59	+.15	+.19
r_{GO}	+.13	−.40	−.25	−.31	−.22
r_{GP}	+.34	−.51	+.31	−.45	−.10
r_{GQ}	−.09	−.32	+.56	−.41	−.05
r_{GR}	−.00	−.48	+.14	−.38	−.19
r_{GS}	+.23	+.21	−.19	+.46	+.17
r_{GT}	−.07	−.16	+.23	−.24	−.06
r_{GU}	+.65	−.03	+.48	−.49	+.15
r_{GW}	+.21	−.40	+.48	.00	+.07
r_{IM}	+.60	+.55	+.38	+.72	+.55
r_{IN}	+.57	+.41	+.21	+.41	+.38
r_{IO}	+.59	+.39	+.29	+.74	+.50
r_{IP}	+.65	+.63	+.60	+.52	+.58
r_{IQ}	+.48	+.64	+.71	+.54	+.58
r_{IR}	+.49	+.42	+.11	+.53	+.37
r_{IS}	+.53	+.48	+.31	+.56	+.45
r_{IT}	+.47	+.49	+.56	+.87	+.62
r_{IU}	+.60	+.78	−.08	+.35	+.45
r_{IW}	+.61	+.75	+.24	+.61	+.55

[a] See text for explanation.

The average correlation between the gains and the estimates by the students was +0.007, or practically zero. This is slightly and

perhaps significantly smaller than the similar correlation found for the staff estimates. The students seemed to attach considerable importance to the things associated with initial weight, but the average correlation between their estimates and initial weight was only +0.51 as contrasted with +0.69 for the staff estimates and initial weight. The average correlation between the estimates of one student and those of all other students was +0.597 as compared with a corresponding figure of +0.583 for the average correlation between staff estimates.

The partial correlation coefficients between gains and estimates, initial weight being constant, differ only slightly from the primary correlation coefficients between estimate and gain. However, the partial correlation coefficients between gain and initial weight, the various estimates being constant, are somewhat larger in the case of the student estimates, which indicates that some of the things reflected in initial weight were not completely taken into account by the students when they made their estimate.

The multiple correlation coefficient between gain as the dependent variable and initial weight and the 10 sets of estimates by students as the independent variables was 0.891, which is very distinctly higher than the corresponding coefficient for the staff estimates. The estimates by the students, which were individually less accurate than those of the staff members, were decidedly more accurate when combined in the multiple correlation coefficient. This seems to mean that the staff members agreed very well with one another in regard to points which actually did have something to do with gain but disagreed on things which were not associated with gain. The total agreement of the students with one another was practically the same as for the staff members, but agreement seemed to be largely on things not actually associated with gain. The students differed in regard to a number of things, some of which were associated positively and some negatively with gain. Thus the combined result of estimating the gain according to their various estimates (giving negative weight to some sets of estimates, of course) is to include all things seen by any of the men regardless of whether they were seen by the others. The accuracy of the staff estimates improved only a little by including things seen by other members of the group, whereas the accuracy of the student estimates increased greatly when to what each student saw was added what every other student saw, whether that other student had interpreted it rightly or wrongly. That initial weight by itself has little importance is shown by the fact that the multiple correlation between gain and the 10 student estimates is 0.880 as compared with 0.891 when initial weight was also included. Not many things actually associated with initial weight escaped the notice of all 10 of the students making these estimates. The 180 original uncorrected correlations between one student's estimate and the estimate of other students were distributed as follows:

−0.50 to −0.59	4	+0.20 to +0.29	7
−0.40 to −0.49	0	+0.30 to +0.39	12
−0.30 to −0.39	1	+0.40 to +0.49	18
−0.20 to −0.29	1	+0.50 to +0.59	24
−0.10 to −0.19	3	+0.60 to +0.69	26
−0.00 to −0.09	6	+0.70 to +0.79	22
+0.00 to +0.09	5	+0.80 to +0.89	32
+0.10 to +0.19	6	+0.90 to +0.99	13

This distribution, like the others, shows very well the asymmetric distribution of correlation coefficients calculated from small samples where the true value of the correlation coefficient is fairly large.

In this experiment, as in the second and third steer experiments, an attempt was made to predict what the steers would be worth per pound on foot when the feeding was ended. The correlations between the estimates by the staff members and final value and initial weight and gain are shown in Table 11.

TABLE 11.—*Correlations between final values and estimates of final values made by staff members at the beginning of the feeding period, fifth experiment with steers*

Symbol [a]	Correlation coefficients concerning final values for—				Averages by Fisher's method
	Choice feeder steers	Good feeder steers	Medium feeder steers	Common feeder steers	
r_{Va}	+0.16	−0.13	+0.61	+0.59	+0.33
r_{Vb}	+.31	+.19	+.04	+.37	+.22
r_{Vc}	+.44	+.58	+.61	+.27	+.47
r_{Vd}	+.51	+.38	+.29	+.70	+.47
r_{Ve}	+.30	−.18	+.51	−.12	+.13
r_{Vf}	+.26	−.50	+.76	+.77	+.40
r_{Vh}	+.54	+.35	+.66	+.44	+.48
r_{Vi}	−.03	+.50	+.83	+.11	+.43
r_{Vk}	+.55	+.15	+.57	+.13	+.34
r_{Vl}	+.45	−.66	+.09	+.63	+.11
r_{VO}	+.71	+.31	+.43	+.20	+.40
r_{VI}	+.38	−.35	−.21	+.54	+.09
r_{Ia}	+.47	+.39	+.48	+.47	+.43
r_{Ib}	+.06	+.01	+.15	+.01	+.05
r_{Ic}	−.32	−.14	−.67	−.22	−.34
r_{Id}	+.74	+.20	+.62	+.77	+.59
r_{Ie}	+.36	+.19	+.62	+.29	+.36
r_{If}	+.54	+.46	+.01	+.38	+.34
r_{Ih}	+.71	+.32	+.41	+.42	+.45
r_{Ij}	−.19	−.35	−.09	−.34	−.23
r_{Ik}	+.63	+.43	−.03	+.39	+.35
r_{Il}	+.84	+.64	+.85	+.88	+.80
r_{Ga}	+.01	−.04	+.38	+.60	+.25
r_{Gb}	+.23	−.27	+.18	−.18	−.02
r_{Gc}	+.28	+.05	−.06	−.44	−.06
r_{Gd}	+.54	−.11	+.67	−.03	+.28
r_{Ge}	+.29	−.15	+.36	−.13	+.09
r_{Gf}	+.34	−.13	+.18	+.25	+.15
r_{Gh}	+.71	+.09	+.32	−.31	+.21
r_{Gi}	−.52	−.03	+.60	+.01	+.05
r_{Gk}	+.48	+.03	+.03	−.21	+.07
r_{Gl}	+.23	−.28	+.55	−.17	+.09

[a] See text for explanation.

The correlations between final value and estimates show the usual variation characteristic of correlations calculated from small samples. However, the average correlation between actual and estimated final values was positive for each set of estimates and the average of these 10 averages was 0.344, which is 0.107 higher than the corresponding figure for the estimates of gain by the same men. This difference is of doubtful significance. However, the difference found here is the same as was found in the second and third steer experiments, and is in line with what would be expected from professional animal husbandmen who had had much more practice in selecting steers that would be desirable for butchering than in picking those that would make large gains As in the other two experiments, the men showed much less agreement among themselves in estimating final values than in estimating

gains. The average of the correlations between estimates made by each man and each of the other men is +0.350. The distribution of the 180 uncorrected correlations between one estimate and another for each lost is as follows:

−0.40 to −0.49	2	+0.30 to +0.39	19
−0.30 to −0.39	5	+0.40 to +0.49	20
−0.20 to −0.29	5	+0.50 to +0.59	19
−0.10 to −0.19	9	+0.60 to +0.69	14
−0.00 to −0.09	10	+0.70 to +0.79	23
+0.00 to +0.09	15	+0.80 to +0.89	4
+0.10 to +0.19	17	+0.90 to +0.99	1
+0.20 to +0.29	17		

The average correlation between initial weight and the estimates was +0.317. The partial correlation coefficients between estimates and final value, initial weight being constant, were practically the same as the corresponding primary coefficients. Whatever success these men had in picking the steers with the high and low final value was not noticeably influenced by whether or not they tended to pick large or small steers in their estimating.

The multiple correlation coefficient between final value as the dependent variable and the 10 estimates of final value and initial weight and gain as the 12 independent variables is 0.811. This falls only to 0.792 when gain is left out and to 0.762 when initial weight is also left out.

The steers used in this experiment were selected because of their close conformity to the market grade which each lot was to represent. It is therefore to be expected that there would be more uniformity in the final value of the steers within each lot than would be the case in many other experiments. The importance of this fact in explaining the actual results may be partly measured by the size of the coefficient of variability for the final values within each lot. The average final value for all 39 steers was 11.11 cents per pound and the average intralot standard deviation (35 degrees of freedom) was 0.68 cent per pound, giving a coefficient of variability of 6.14 per cent. This figure is distinctly lower than that found for the variability of gain, but is actually higher than in the second and third steer experiments, where there was no such rigid selection for feeder grade at the beginning of the experiment. An additional clue is perhaps furnished by the average values between lots, which were: Choice steers, 12.43 cents per pound; good steers, 11.66; medium steers, 10.41; and common steers, 10.05. The variance per degree of freedom between lots is nearly three times as great as it is within lots, thus indicating (although the amount of data is too small to be considered convincing) that a very large portion of the differences in final value between the whole group of four lots of steers had been seen in advance and discounted when the steers were divided into lots according to their feeder grade.

The correlation studies reported here bear only on those differences in final value which existed between steers in the same lot. Therefore they fail to show how much of the variation in final market value of all kinds of steers could have been predicted by these men. These correlation studies do indicate, however, that between steers given the same market grade as feeders there were still a few small differ-

ences which could be foreseen by the men who studied them. Of course in most ration tests the steers used would all come within the same market grade or close to it.

The student estimates of final value had a slightly lower correlation with the actual values than the estimates made by the staff members, although the difference is so small that it does not even approach significance in the statistical sense of the word. The original and average correlations between the student estimates and final value and gain and initial weight are shown in Table 12.

TABLE 12.—*Correlations between final values and estimates of final values made by students at the beginning of the feeding period, fifth experiment with steers*

Symbol [a]	Correlation coefficients concerning final values for—				Averages by Fisher's method
	Choice feeder steers	Good feeder steers	Medium feeder steers	Common feeder steers	
rV_m	+0.03	−0.45	+0.22	+0.64	+0.13
rV_n	+.14	−.13	+.78	+.85	+.52
rV_o	+.16	−.08	+.52	+.75	+.37
rV_p	+.16	−.60	+.17	+.71	+.13
rV_q	+.14	−.32	+.66	+.57	+.30
rV_r	−.20	−.25	+.74	+.48	+.25
rV_s	+.16	−.45	+.53	+.65	+.25
rV_t	−.09	−.36	+.69	+.76	+.33
rV_u	+.44	−.55	+.03	+.63	+.14
rV_w	+.10	−.64	+.77	+.58	+.24
rI_m	+.45	+.26	+.15	+.70	+.40
rI_n	+.36	+.23	−.27	+.47	+.19
rI_o	+.56	+.29	+.11	+.71	+.42
rI_p	+.52	+.66	+.71	+.30	+.55
rI_q	+.57	+.55	+.03	+.25	+.35
rI_r	+.45	+.29	−.30	+.24	+.15
rI_s	+.43	+.38	+.13	+.56	+.37
rI_t	+.58	+.34	+.20	+.78	+.49
rI_u	+.56	+.57	+.43	+.75	+.57
rI_w	+.57	+.57	−.16	+.56	+.39
rG_m	+.07	−.29	+.57	−.35	+.01
rG_n	+.43	−.56	+.31	+.12	+.05
rG_o	+.10	−.40	−.20	−.31	−.21
rG_p	−.05	−.61	+.21	−.20	−.18
rG_q	+.19	−.20	+.70	−.42	+.09
rG_r	−.19	−.49	−.06	−.04	−.19
rG_s	+.29	−.22	.00	−.05	−.01
rG_t	−.10	−.38	+.21	−.30	−.14
rG_u	+.61	−.09	+.39	−.16	+.18
rG_w	+.16	−.52	+.11	−.16	−.12

[a] See text for explanation.

The average correlation between student estimates and actual final values was +0.270, while that between estimates and initial weight was +0.395. The distribution of the 180 original uncorrected correlation coefficients between one set of estimates and another set is as follows:

−0.40 to −0.49	1	+0.30 to +0.39	18
−0.30 to −0.39	0	+0.40 to +0.49	17
−0.20 to −0.29	1	+0.50 to +0.59	25
−0.10 to −0.19	0	+0.60 to +0.69	26
−0.00 to −0.09	3	+0.70 to +0.79	23
+0.00 to +0.09	9	+0.80 to +0.89	33
+0.10 to +0.19	10	+0.90 to +0.99	7
+0.20 to +0.29	7		

The tendency of the students to agree with each other in their estimates of the final value of steers was more pronounced than the corresponding tendency among the staff members, the two averages being +0.593 and +0.350, respectively. This difference probably approaches significance, although in the absence of an entirely accurate means of estimating the degrees of freedom lost in using each estimate nine times in the comparisons with the other estimates, one is perhaps not justified in concluding that the difference is significant.

The multiple correlation coefficient between final value as the dependent variable and the 10 student estimates and initial weight and gain as the independent variables is 0.774. When gain is omitted the multiple correlation coefficient with the other 11 independent variables falls to 0.718. When initial weight is also left out of consideration and only the 10 sets of estimates are used as independent variables, the multiple correlation coefficient falls from 0.718 only to 0.716. The first-order partial correlation coefficients show that practically all of the things associated with initial weight which were also associated with final value, were seen and taken into account by nearly all of the 10 students who made the estimates. The average correlation between the student estimates of final value and the actual gain was 0.052.

DISCUSSION

The results of the eight experiments recorded in this paper agree so well that certain conclusions appear to be unavoidable in spite of the handicaps of extremely small lots and statistical methods not quite perfectly adapted to the problem. One of these conclusions is that a high correlation existed between initial weight and the estimates of gain. This averaged +0.904 in the pig experiments and +0.699 in the steer experiments. Presumably it is not weight as such which influences the judges, but the broader concept of size as indicated by bigness of frame and vigorous "growthy" appearance. It is not unusual to hear disparaging remarks about the average farmer's stock-judging ability because he frankly lays so much emphasis on size. And yet when it comes to estimating gains, these figures seem to show that the professional animal husbandman himself attaches considerable importance to size. That this is partially justified is shown by the rather general tendency of initial weight to be correlated with gain. However, this correlation was not found in the first pig experiment nor in the fourth steer experiment.

The correlation between initial weight and gain was much larger in the second and third pig experiments than in any of the steer experiments. In an unpublished study by H. H. Mitchell, of the Illinois station (to whom the writer is indebted for permission to mention the results), the same difference between pigs and steers is noted. Mitchell found a generally high and significant correlation between initial weight and gain in published reports of feeding experiments with pigs at many stations, and a generally low or quite insignificant correlation between initial weight and gain in those experiments with steers in which sufficient data were given to permit the calculation of this correlation. The reasons for the higher correlation in pig experiments are not clear, but the following points may have some bearing on the problem: (1) Pigs are usually born and raised at the station where they are fed, while most steers are

purchased, and sometimes those in a single experiment come from several different places; (2) pigs are distributed by litters and thereby achieve a more perfect balancing with respect to hereditary differences than is usually possible with steers; (3) the variability in age and size of pigs at the beginning of the experiments is often (though not always) greater than that in the groups of steers started on feed; (4) pigs have a relatively simple digestive system as compared to that of ruminants and their capacity for consuming feed may be more closely and directly related to their size than is the case with steers.

Severson and Gerlaugh (*9*) reported a correlation of only +0.036 between initial weight and gain of 338 steers fed at the Pennsylvania station during eight years. Their data were all grouped together in a single table, and consequently were affected by heterogeneity of mean weights and mean gains for the various lots. Had a correction been made for this heterogeneity the correlation would almost certainly have been somewhat larger.

Data on seven lots of steers fed at the Texas station before the experiments herein reported were begun give an average correlation (by Fisher's method (*2*)) of +0.333 (44 degrees of freedom) between initial weight and gain. All but 5 of the 67 steers used in the experiments were bred and raised at the station. When the data for these 67 steers are combined with the data presented in this study an average correlation of +0.240 is found between initial weight and gain. This figure is based on data from 320 steers, but since they were fed in 33 separate lots and three degrees of freedom are lost for each additional lot into which they were separated, it is as reliable as if calculated on a single lot of 224 steers about as uniform as the average uniformity within each lot actually fed.

The correlation between initial weight and estimates of value was +0.420 (three experiments only, but 798 degrees of freedom if each estimate is counted independently of other estimates made on the same steers), which is distinctly less than was found between initial weight and estimates of gain but is large enough to be of undoubted statistical significance. The average correlation between initial weight and actual final value was +0.386 (111 degrees of freedom). The average correlation between estimates of final values and actual final values was +0.334 (798 degrees of freedom, if each estimate is counted independently of other estimates made on the same steer). The average correlation between estimates of final value made by different men was +0.488 (apparently 2,739 degrees of freedom but many of these were spurious because each estimate was used as many times as there were other estimates on the same steer), which is distinctly less than the corresponding correlations between estimates of gain. This rather slight agreement on the ideal type for high final value and fairly close agreement on the ideal type for large gains is all the more surprising because so much of the formal instruction in stock judging concerns the ideal butcher type and so little of it deals directly with the ideal feeder type. Nevertheless, although the men agreed with one another less closely in estimating final value than in estimating gain, they were slightly more successful in estimating final value.

It is conceivable that the usual variation in gains or in final value might be the sum of a rather constant unpredictable amount of variation and a certain variable amount which good judges would be

able to foresee. If this were true then the correlation between judgment and gain or final value should be high in those experiments in which gains or final values were quite variable and low in those experiments in which the gains or final values were very uniform. In other words, judges could foresee not a certain proportion of all variability in performance but a certain proportion (or all) of that above a minimum amount, which must be regarded as unpredictable. The data do not support this hypothesis, although, since only eight experiments were included, the evidence can hardly be considered conclusive. Thus, as Table 13 shows, the most successful estimates of pig gains were attained in the experiments in which the gains were most uniform, and the least successful estimates of steer gains were attained in the experiment in which gains were most uniform and in the experiment in which gains were least uniform. The degree of success in estimating final value does support this hypothesis fairly well, but the differences are small and only three experiments were included.

TABLE 13.—*Summary of results from the eight experiments showing degree of success attained in forecasting individual gains and final values*

Description of experiment	Men making estimates	Data equivalent to calculations upon a single lot of animals	Percentage determination ($100\ R^2$) of gain or final value—		Reduction in coefficient of variation if lots had been composed of animals identical in weight and in the eyes of all the men who made the estimates (from C. V. to C. V. $\sqrt{1-R^2}$)
			By initial weight and all estimates	By initial weight and the one set of estimates having the highest primary correlation with gain or with final value	
EXPERIMENTS IN ESTIMATING GAINS					
	Number				*From To*
First with pigs	[a]3	28	10.6	10.6	13.3–12.6
Second with pigs	3	48	50.0	46.6	9.8– 6.9
Third with pigs	[b]	61	49.3	46.9	12.1– 8.6
First with steers	1	43	8.8	8.8	10.6–10.1
Second with steers	4	48	18.3	15.2	12.0–10.8
Third with steers	2	42	16.6	16.2	15.8–14.4
Fourth with steers	11	31	54.2	11.3	12.2– 8.3
Fifth with steers	[c]10	30	39.4	14.4	14.9–11.6
Fifth with steers	[d]10	30	79.4	3.9	14.9– 6.8
EXPERIMENTS IN ESTIMATING FINAL MARKET DESIRABILITY					
Second with steers	4	48	34.2	31.9	5.49–4.55
Third with steers	2	42	22.3	22.3	4.10–3.61
Fifth with steers	[c]10	30	62.7	23.3	6.14–3.75
Fifth with steers	[d]10	30	51.6	27.1	6.14–4.26

[a] As a committee. [b] 4 with 3 repeating. [c] Staff members. [d] Senior students.

It will be seen from Table 13 that as a whole the success of the men in estimating gains was quite limited. In 4 experiments about one-half of all the causes of differences in gains were foreseen, in 2 experiments about one-sixth, and in 2 experiments about one-tenth. But in the second and third experiments with pigs, initial weight was so

closely associated with gain and with the judgments that the men would have had only a little additional success if they had been making estimates on a group of pigs already balanced according to weight.

The statistical procedure of combining in a multiple correlation coefficient the estimates of many different men where the lots were few and small and where average coefficients had to be used may not be perfectly valid. The method of averaging does not rest upon an absolutely rigid mathematical relation, and the approximate corrections for small size of the samples are based upon an average bias which will not prevail in every sample without exception. Probably no serious error is thereby introduced into the average simple correlation coefficients, but such errors might possibly be cumulative and become fairly large in such experiments as the third with pigs or the fourth and fifth with steers. To explore this possibility the figures in column 5 of Table 14 were prepared, using for independent variables initial weight and in each experiment that set of estimates which was most closely correlated with gain or with final value. This procedure, of course, will show more effect of balancing in most experiments than is justified, since the set of estimates to be used was picked out after the experiment was over.

The figures may be considered as representing the combined effect of balancing according to initial weight and according to the opinion of one unusually good judge. The differences between these figures and those in the preceding column are slight except for the gains in the fourth and fifth steer experiments and the final values in the fifth steer experiment (these were the only experiments in which more than four men made estimates). This tends to confirm the idea that the very high R^2 found in those two experiments is misleading. Everything seen by even one man is included if correlated with the dependent variable, whether the correlation was in the direction the man thought or opposite to it. Naturally the inclusion of estimates by more and more men would almost inevitable result in additions to R^2. R^2 might thus become very high without any one of the men having been really very successful in his estimates. This seems to have been exactly what happened with the student estimates of gain in the fifth steer experiment, in which many of the average primary correlation coefficients were negative. For these reasons it is believed that the figures in column 5 of Table 13 present a truer picture than do those in column 4. A larger figure for student estimates of gain would have been obtained in column 5 if the estimates of the student having the largest negative correlation with gain had been used instead of the estimates of the student having the largest positive correlation.

Only a small reduction in the amount of experimental error in the feeding trial would result if all the animals should weigh identically the same and be so nearly alike that the men in charge could not tell them apart. Apparently it is a rare experiment in which the variation under such extreme conditions would be reduced to much less than 75 or 80 per cent of what it actually is. More often the effects of balancing are so slight that the variation not foreseen or discounted in the balancing is at least 90 per cent as large as the gross observed variation. This of course does not mean that balancing should be omitted. On the contrary the fullest possible use should be made of

it. Anything it actually does accomplish is just so much gained and there is no possibility of doing harm by using it, even negative correlations between estimates and performance having a beneficial effect in helping to distribute the desired qualities equally. But it is important that we should not conclude that two lots are exactly comparable merely because careful and painstaking efforts were made to divide them so. It appears that in general the men saw the causes of gain which were associated with size and that they saw also a few of the other causes, but that most of the other causes of differences in gain were either not associated with any visible characteristics of the steers or the men did not know what those visible characteristics were.

Very little difference was found in the ability of various men to estimate gains or final values correctly. None of the differences found were statistically significant. However, the data were too few to prove the reality of small differences of this kind. Many of the differences observed in predicting ability seemed rather extreme, but were reversed on the next group of animals or in the next experiment. This conclusion, like the others, applies only to the range of data and of men included in this study. The estimating of gains and final values as practiced in these experiments was of course quite different from judging breeding animals as practiced at shows and fairs.

The question as to whether the men who made these estimates were representative of animal husbandmen in general can not of course be answered objectively. It may, however, be pointed out that the agricultural colleges at which they received their undergraduate training included seven—Kentucky, Indiana, Kansas, Ohio, Ontario, Wyoming, and Texas—and that one or more of them had done graduate work at the following institutions: Illinois, Iowa, Kansas, Missouri, Texas, and Wisconsin.

The coefficients of variation found in these eight experiments were in every case smaller than the average found by Mitchell and Grindley *(8)*, in spite of the fact that the *n–1* formula used in calculating the standard deviations in this study tends to give slightly higher figures than would be obtained by the formula which they used. As a partial explanation of this fact it may be noted that all these gains were reasonably good ones, and of course a large gain is to some extent associated with a small coefficient of variability, inasmuch as the latter is a fraction of which the former is the numerator.

Finally, it should be repeated that one probable cause of variation in gains was outside the scope of this study; namely, variations in the amount of feed eaten. It is possible that this factor may have been the cause of all the observed correlations between initial weight and gain or between judgment and gain. If such were the case it would of course have a very important bearing on the significance of observed differences between lots, especially where differences in feed consumption are taken into account. The only means of attack on this problem seems (to the writer) to be an extensive series of individual feeding experiments paralleled by groups fed in the ordinary manner on the same rations as the individually fed animals and during the same periods.

SUMMARY AND CONCLUSIONS

The relative gains of individual pigs and steers used in regular feeding experiments were estimated at the beginning of a series of experiments by members of the staff of the Texas Agricultural and Mechanical College and the agricultural experiment station. In three of the experiments with steers the men estimated also what the relative market desirability of the individual steers in each lot would be when fattening was completed. Both kinds of estimates were made relative to the performance of other individuals in the same lot, so as to eliminate the effects of changing price levels and of differences in the rations fed. The correlations found between those estimates, initial weights, and actual performance were then studied.

Differences in initial weight were only slightly correlated with differences in gain in the case of steers (average $r = +0.24$, based on the statistical equivalent of one lot of 224 steers), but they were distinctly correlated with gain in the case of pigs (average $r = +0.52$, based on the statistical equivalent of one lot of 128 pigs). Published data support the conclusion that the correlation between initial weight and gain is normally higher with pigs than with steers.

The average correlations between estimates and gains in the three pig experiments were: $+0.05$, $+0.63$, and $+0.64$. The average correlations between estimates and gains in the five steer experiments were: -0.03, $+0.33$, $+0.33$, $+0.04$, $+0.24$, and (for students) $+0.01$. The average correlations between estimated and actual final values were $+0.42$, $+0.32$, $+0.34$, and (for students) $+0.27$.

The correlations mentioned in the two preceding paragraphs are large enough to be significant and to demonstrate the desirability of balancing lots at the beginning of experiments as carefully as possible, but they are not high enough to account for a very large fraction of the observed variations in gains or in final value.

The proportion (squared multiple correlation) of the causes of gain which were associated either with differences in initial weight or with things seen by the man who made the most successful set of estimates in a particular experiment ranged from 3.9 to 16.2 per cent for gains in the steer experiments, from 10.6 to 46.9 per cent for gains in the pig experiments, and from 22.3 to 31.9 per cent for final values in the steer experiments. Where the estimates of several men were included as additional independent variables the squared multiple correlation coefficients were larger of course, but much of this was due to the limited amount of data used.

The estimates were closely correlated with initial weight, especially in the experiments with pigs. Most of the men saw something more in the animals than was reflected in initial weight, but there were several cases of negative partial correlation coefficients between estimate and gain, initial weight being constant.

In three experiments where final value was estimated, the estimates were slightly more successful than the estimates of gain.

The most impressive finding in these experiments is the large amount of variation in gain and also in final value that was not foreseen by trained men who spent much time in close study of the experimental animals. Perhaps the major factors that determine which individuals will make large and which small gains, or which will be worth most and which will be worth least when the experiment is

over, are not after all closely associated with visible differences in the animals.

In the experimental work each lot was treated as a unit complete within itself, and therefore the findings here reported apply only to the range of differences included within a single lot of animals. It is quite likely that higher correlations would have been found if each lot had included a wide range of animals varying greatly in size, age, and market grade, but such variations are not often found among animals in modern feeding experiments.

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THE CALCIUM REQUIREMENTS OF DAIRY HEIFERS[1]

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INTRODUCTION

For several years (1922–1928) investigations were carried on at this station to determine the value of mineral supplements in the rations of dairy cows. When a study was made of the literature in connection with this problem it was discovered that very little information is on record relative to the mineral requirements of dairy animals, more particularly of young stock. Because of this fact it was difficult to measure the adequacy in this respect of different types of rations. Accordingly a project was organized in 1927 the aim of which was to determine, if possible, the calcium and phosphorus requirements of dairy heifers from the time they are weaned from milk (5 to 6 months) until they freshen the first time (28 months or thereabouts). It was thought that at the very least it would be possible, with the results secured, to determine whether or not average rations which are fed in practice to dairy heifers carry sufficient mineral matter for proper growth.

EXPERIMENTAL ANIMALS

The calcium requirements were the first to be investigated and for this purpose eight high-grade Holstein heifers were used.[2] They were divided into two groups; one group was fed a ration high in calcium, the other was fed a ration low in calcium. The history of these heifers is shown in Table 1.

TABLE 1.—*History of the heifers used in the calcium requirement tests*

Group	Heifer No.	Born	Age at commencement of experiment	First calf delivered	Age at first calving
			Days		*Days*
High-calcium ration	121	Aug. 30, 1926	136	Dec. 14, 1928	837
	[a] 125	Sept. 17, 1926	131		
	131	Jan. 27, 1927	278	June 20, 1929	875
	137	July 24, 1927	161	Oct. 30, 1929	829
	139	Aug. 5, 1927	149	Dec. 29, 1929	877
Average			[b] 144		855
Low-calcium ration	126	Oct. 2, 1926	132	Feb. 16, 1929	868
	[c] 128	Nov. 2, 1926	119	July 30, 1929	1,001
	138	July 29, 1927	156	Dec. 11, 1929	866
	141	Aug. 27, 1927	139	Dec. 22, 1929	848
Average			137		[d] 861

[a] Died at 13 months; No. 131 substituted for her.

[b] Average does not include No. 131.

[c] It was unfortunate that No. 128 calved at a much later age than any of the others. She was bred in the spring of 1928 and not showing heat three weeks later was presumed to be with calf, and was sent to pasture. It was not discovered that she was not with calf until she returned from pasture in September, and some difficulty was then experienced in getting her bred.

[d] Average does not include No. 128.

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[2] One of these died of acute tympany at 13 months of age, and another heifer that had been held in reserve was substituted for her.

EXPERIMENTAL FEEDING

The general nature of the rations was as follows:

High calcium ration	Low calcium ration
Alfalfa hay.	Hay from mixed grasses.
Some mixed hay.	Alfalfa (small amount, first year).
Dried beet pulp.	Dried apple pomace.
Low protein concentrate mixture (corn meal for the most part).	High protein concentrate mixture (usually corn meal supplemented with linseed meal).

During the first period of six months the high-calcium group received approximately two-thirds alfalfa and one-third mixed hay; during the second period, from September, 1927, to June, 1928, the roughage was largely alfalfa; during the third and fourth periods (October, 1928, to June, 1929, and September to December, 1929) alfalfa averaged about 60 per cent and mixed hay about 40 per cent of the hay ration.

The roughage for the low-calcium group consisted entirely of mixed hay except in the first period (March to June, 1927), when alfalfa constituted about one-third of the roughage. These adjustments were necessary in order to keep the amount of calcium fed to the two groups at the proper level.

CHARACTER AND COMPOSITION OF FEEDS

The alfalfa was a California product of excellent quality. The hay was grown on the college grounds and consisted of a mixture of grasses. Beet pulp and the several concentrates composing the two mixtures were purchased in the open market and were of good average quality. The apple pomace was secured from a cider manufacturer in a near-by town and was dried with the aid of modern machinery. The composition of the various feeds is shown in Table 2.

TABLE 2.—*Percentage composition of feeding material used in the experiments*

Number of analyses	Material	Moisture			Nitrogen			Ash		
		Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
8	Low protein concentrate mixture	10.34	14.40	12.33	1.849	2.007	1.904	2.78	2.99	[a]2.86
5	High protein concentrate mixture	8.46	11.87	10.38	3.191	3.404	3.322	3.10	3.70	[b]3.42
15	Alfalfa hay	8.50	11.68	9.82	2.380	3.555	2.701	7.36	9.85	[c]8.27
17	Mixed hay	7.28	10.93	9.32	.890	1.789	1.205	4.60	6.28	[c]5.10
5	Dried apple pomace	5.85	11.85	9.50	.752	1.003	.846			[d]2.43
9	Dried beet pulp	7.88	12.25	9.93	1.225	1.577	1.432	3.65	3.95	[c]3.81

Number of analyses	Material	Calcium			Phosphorus			Magnesium		
		Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
8	Low protein concentrate mixture	0.028	0.070	0.048	0.379	0.432	0.414	0.124	0.190	0.157
5	High protein concentrate mixture	.055	.087	.073	.475	.563	.509	.202	.242	.219
15	Alfalfa hay	1.074	1.536	1.272	.218	.313	.247	.280	.480	.346
17	Mixed hay	.403	.537	.488	.110	.285	.176	.119	.209	.158
5	Dried apple pomace	.112	.197	.155	.080	.111	.099	.048	.060	.055
9	Dried beet pulp	.468	1.125	.843	.061	.104	.077	.232	.347	.284

[a] 6 determinations. [b] 5 determinations. [c] 7 determinations. [d] 1 determination. [e] 3 determinations.

The high-calcium ration supplied about twice as much of that element as did the low calcium-ration. An attempt was always made to keep the other constituents of both rations as nearly on a par as possible, although it was found somewhat difficult to do this in practice. The beet pulp was included partly because of its calcium content and partly to furnish succulence and palatability. The apple pomace served the latter purpose admirably in the low-calcium ration and carried very little mineral matter. The high protein content of the alfalfa was offset by feeding to the heifers in the low-calcium group a grain mixture somewhat higher in protein. For the most part this was done by simply adding linseed meal to their ration in small amounts. The standard used in adjusting the rations for protein and energy was that given by Armsby [3] for dairy cattle. For lack of something more specific Kellner's mineral standard [4] was used as a general guide in determining the levels of calcium to feed, but it can not be regarded as particularly applicable since it was devised for mature cows. It calls for a daily minimum intake of 3.25 gm. of calcium and 1 gm. of phosphorus for each 100 pounds of live weight. The detailed intake of nutrients by both groups at different periods throughout the experiment is set forth in Table 3.

TABLE 3.—*Intake of total nutrients by heifers, per 100 pounds live weight*

Period	Group	Intake (in pounds daily per 100 pounds live weight) of—						
		Dry matter	Protein	Crude fiber	Nitrogen-free extract	Fat	Calcium	Phosphorus
March–June, 1927	High calcium	2.04	0.27	0.50	1.09	0.047	0.019	0.005
	Low calcium	2.16	.29	.49	1.20	.069	.011	.007
September, 1927–June, 1928.	High calcium	1.69	.25	.33	.95	.043	.015	.004
	Low calcium	1.73	.22	.42	.94	.059	.007	.005
September, 1928–June, 1929.	High calcium	1.46	.19	.31	.84	.035	.011	.003
	Low calcium	1.60	.19	.37	.91	.057	.006	.004
September–December, 1929.	High calcium	1.51	.20	.34	.85	.042	.012	.004
	Low calcium	1.57	.16	.37	.94	.057	.007	.004

The periods in Table 3 represent the intervals of time during which mineral balance trials were being carried on with the heifers. During July and August of each year the heifers were on pasture. The intake of digestible protein and the net energy during the above-mentioned periods are shown in Table 4.

TABLE 4.—*Intake of digestible protein by heifers and net energy per 100 pounds live weight*

Period	Group	Digestible protein (pounds daily)	Net energy (therms daily)
March–June, 1927	High calcium	0.18	1.14
	Low calcium	.20	1.23
September, 1927–June, 1928	High calcium	.15	1.06
	Low calcium	.15	1.06
September, 1928–June, 1929	High calcium	.13	.91
	Low calcium	.11	.95
September–December, 1929	High calcium	.13	.90
	Low calcium	.09	.92

[3] ARMSBY, H. P. THE NUTRITION OF FARM ANIMALS. Table IV (b), p. 713. New York. 1917.
[4] KELLNER, O. DIE ERNÄHRUNG DER LANDWIRTSCHAFTLICHEN NUTZTIERE. Aufl. 8, Berlin, p. 618. 1919.

It will be noted that during the last two periods shown the low-calcium group received less digestible protein than the high-calcium group, the difference increasing somewhat as the animals became older. The difference was unavoidable since it was desired to supply both groups the same amount of net energy per unit of weight and at the same time keep the level of calcium intake, derived largely from alfalfa, somewhat higher than in the low-calcium group. To be explicit, as heifers approach maturity their protein requirements increase little, if any, while their energy requirements continue to increase. This creates a situation which renders accurate balancing of rations impossible where alfalfa hay, with its high protein content, is fed. In order to insure a sufficient intake of energy an excess of protein must be fed. It was necessary to feed alfalfa hay to the high-calcium group in order to keep the level of calcium intake somewhat higher than that in the low-calcium group; hence the spread between the two groups in intake of digestible protein, which became more noticeable as the average age of the heifers increased.

METABOLISM BALANCE TRIALS

Mention has already been made of the metabolism balance trials which were carried on. This phase of the investigation was perhaps the most important in the whole program. Eighty-four of these trials were carried through. During the trials the heifers were kept in specially constructed stalls arranged for convenient collection of urine and feces. These stalls were made adjustable so as to accommodate the heifers from the time they were small calves until they were full grown. This was accomplished by sliding the stanchion and manger backwards or forwards and by employing portable side pieces which were used when the animals were small and removed as they grew older, leaving the full width of the stall for the larger animals. (Fig. 1.) The animals were kept in the stalls from 12 to 14 days for each trial, the first 2 to 4 days being a preliminary period to allow them to become accustomed to the routine. The last 10 days of each period constituted the experiment proper, and during this time the urine and feces were collected daily. Each animal stood on heavy waterproofed sailcloth, under which, as an extra protection against loss of urine, there was placed a strip of rubber matting extending the full length and width of the stall. Underneath that was a layer of shavings about 2 to 3 inches thick. The floor of the stall was covered with galvanized sheet iron and the entire stall was given a slight pitch to the rear so as to insure free drainage into the collection hopper, which was also lined with galvanized iron. The hopper fitted snugly to the rear of the stall and was easily removable when the animals were put up or taken down. The urine and feces were collected in large galvanized-iron pails placed underneath the hoppers. Each morning at 8.30 during the course of a trial the pails were removed and weighed, and the urine and feces thoroughly mixed with a wire beater. A 10 per cent sample of the 24-hour output of each animal was then carefully taken, placed in a friction-cover tin pail, and taken at once to the laboratory where it was subsampled down to 1 per cent of the 24-hour output. The laboratory samples were preserved in glass-stoppered 2-liter jars with chloroform and refrigeration, each day's sample being added to the composite. At

the end of the period total nitrogen was determined at once on quadruplicate charges of the fresh composite sample, and triplicate charges were ashed in the wet way with sulphuric and nitric acids. The solutions thus obtained were preserved in volumetric flasks and later analyzed for calcium, phosphorus, and magnesium. All feeds were carefully sampled and analyzed, and all waste feed was accounted for, although it should be noted that very little feed was ever wasted.

The nitrogen balances were determined in order to have a criterion of normal growth. The magnesium balances were followed in order to ascertain if possible what interrelation, interdependence, or antagonism existed between the metabolism of this element and that of calcium.

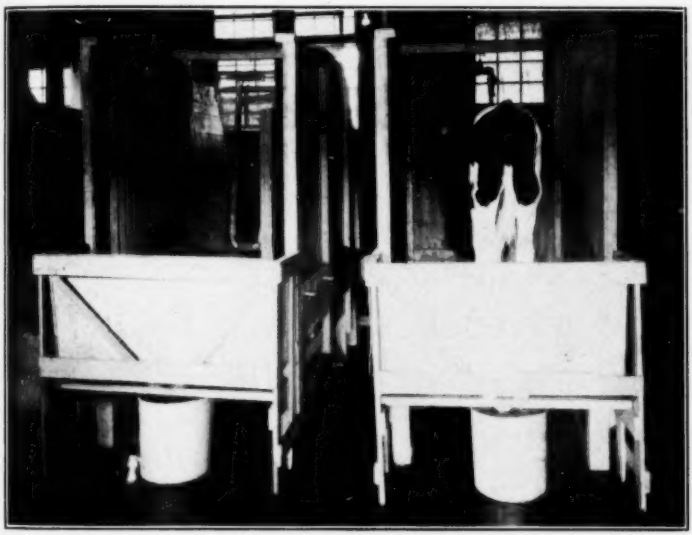

FIGURE 1.—Rear view of metabolism stalls; the unoccupied stall has the removable side pieces in position

Of the 84 trials completed, results from 76 were employed in making the final summary. Either because of known laboratory errors, or because of such abnormalities of the animals as poor appetite or foul smelling, very apparently abnormal feces, results from the other 8 have not been included. Table 5 shows the distribution of the trials between groups and individuals.

TABLE 5.—*Distribution of metabolism trials between groups and individual heifers*

Group	Number of times use was made of heifer No. —								
	121	125	131	137	139	126	128	138	141
High calcium	9	4	9	10	7				
Low calcium						10	11	8	8

The detailed balance records for the individual heifers are given in Table 6. The summarized data appear in Table 7. Considerable fluctuations occurred in the amounts of the several elements stored. Oftentimes these were much greater in different trials with the same animal than between different animals in the same group or between the two groups.

TABLE 6.—*Detailed balance record for each heifer in the mineral metabolism experiment*

HIGH-CALCIUM GROUP

Heifer No.	Actual retention in grams daily of—				Retention per 100 pounds live weight in grams daily of—				Retention as percentage of intake of—			
	N	Ca	P	Mg	N	Ca	P	Mg	N	Ca	P	Mg
121	17.278	8.764	5.545	−0.133	4.320	2.191	1.386	−0.033	19.96	23.45	50.76	−1.17
	11.779	5.631	4.958	2.052	2.752	1.316	1.158	.479	13.51	14.96	45.17	18.19
	29.816	6.983	1.716	1.839	4.969	1.164	.286	.307	28.83	18.29	15.33	13.33
	21.882	1.496	2.697	−.084	3.678	.251	.453	−.014	21.16	3.92	24.09	−.60
	34.816	10.424	4.392	2.602	5.398	1.616	.681	.403	32.20	26.01	37.59	17.82
	17.417	7.794	3.639	−.085	2.219	.993	.464	−.011	16.11	19.45	31.14	−.58
	21.801	9.453	6.018	4.940	2.565	1.112	.708	.581	17.92	20.09	44.82	29.76
	16.143	14.523	2.279	−1.779	1.682	1.513	.237	−.185	12.58	30.83	15.47	−9.38
	19.179	7.260	1.813	−3.186	1.579	.598	.149	−.262	12.14	12.37	11.10	−13.12
Average	21.123	8.036	3.673	.685	2.935	1.117	.510	.095	18.92	18.82	29.48	4.60
125	10.692	7.118	4.851	−.269	3.240	2.157	1.470	−.082	14.19	22.77	49.52	−11.79
	10.496	5.760	5.081	1.420	2.957	1.623	1.431	.400	13.91	18.38	51.79	14.93
	16.386	5.598	4.885	−.020	3.767	1.287	1.123	−.005	19.07	15.10	45.37	−7.59
	27.855	3.689	1.855	.627	5.306	.703	.353	.119	27.74	10.16	16.82	4.77
Average	16.357	5.541	4.168	.440	3.977	1.347	1.103	.107	19.41	16.30	40.26	4.07
131	26.580	6.487	2.532	.359	5.842	1.426	.557	.079	29.17	18.30	24.83	2.97
	17.781	8.327	3.767	−.860	3.666	1.717	.777	−.177	19.51	23.49	36.94	−6.64
	15.678	11.572	3.599	3.738	2.703	1.995	.621	.644	14.74	26.43	34.62	25.58
	15.934	16.351	3.240	−1.923	2.276	2.336	.463	−.275	14.09	37.29	27.69	−11.23
	16.788	4.434	8.03	−1.521	1.908	.504	.091	−.173	13.30	11.15	6.07	−8.72
	31.349	2.157	4.756	−1.680	3.283	.226	.498	−.176	20.41	4.26	27.56	−8.06
	24.685	7.433	3.553	−3.641	2.329	.701	.335	−.343	15.26	14.18	19.15	−15.62
	34.491	4.188	3.712	−1.677	2.961	.359	.319	−.144	18.88	7.59	19.60	7.38
	35.077	6.128	1.586	−1.870	2.998	.524	.136	−.160	20.26	10.76	10.48	−.834
Average	24.263	7.453	3.061	−1.008	2.931	.900	.370	−.122	18.21	16.22	21.93	−4.16
137	24.179	4.610	4.895	5.076	7.218	1.376	1.461	1.515	26.67	13.30	53.98	42.63
	22.972	9.955	4.201	4.387	5.672	2.458	1.037	1.083	23.60	28.68	40.49	35.11
	14.911	14.189	3.301	−2.944	3.062	2.914	.678	−.605	15.32	40.86	31.82	−19.07
	32.490	3.370	3.323	−.433	4.303	.446	.440	−.057	26.92	8.84	27.37	−2.86
	25.898	5.387	2.891	−.528	2.977	.619	.332	−.061	20.08	12.66	20.29	−3.12
	17.232	6.285	3.882	−1.055	1.833	.669	.413	−.112	12.21	13.87	23.99	−5.65
	36.300	9.113	2.254	.738	3.821	.959	.237	.078	24.03	18.58	16.74	4.07
	50.626	5.606	4.635	−1.072	4.801	.542	.448	−.104	30.28	10.23	31.68	−5.13
	39.955	7.743	2.795	4.184	3.632	.704	.254	.380	24.15	12.50	14.93	17.51
	47.558	9.772	4.264	−.881	4.030	.828	.361	−.075	28.74	15.77	22.78	−3.56
Average	31.212	7.603	3.644	.747	3.874	.944	.452	.093	23.55	16.61	26.42	4.36
139	21.392	9.239	3.509	4.420	6.026	2.603	.988	1.245	24.50	26.80	40.51	38.06
	17.036	12.736	3.739	−1.466	4.206	3.145	.923	−.362	17.81	36.69	37.22	−10.61
	21.553	15.282	2.565	−.507	4.145	2.939	.493	−.098	21.47	41.75	24.34	−3.71
	25.111	2.648	3.644	−.567	3.639	.384	.528	−.082	23.48	7.61	34.72	−4.06
	48.528	4.985	3.593	−1.030	5.392	.554	.399	−.114	31.44	9.11	29.32	−5.23
	36.691	5.775	2.739	1.060	3.822	.602	.285	.110	24.75	10.24	16.51	4.90
	37.694	13.537	3.895	.481	3.677	1.321	.381	.047	25.42	23.99	23.48	2.22
Average	29.715	9.172	3.383	.342	4.286	1.323	.488	.049	24.73	20.84	27.80	2.13
Group average	25.488	7.739	3.523	.223	3.490	1.060	.482	.031	21.12	17.76	27.36	1.42

TABLE 6.—*Detailed balance record for each heifer in the mineral metabolism experiment*—Continued

LOW-CALCIUM GROUP

Heifer No.	Actual retention in grams daily of—				Retention per 100 pounds live weight in grams daily of—				Retention as percentage of intake of—			
	N	Ca	P	Mg	N	Ca	P	Mg	N	Ca	P	Mg
126	15.432	4.586	2.896	−0.620	4.978	1.479	0.934	−.200	21.93	26.75	29.07	−8.53
	6.765	2.258	3.857	−.220	1.961	.654	1.118	−.064	8.42	11.30	33.97	−3.80
	12.477	3.812	4.281	.202	2.936	.897	1.007	.048	15.53	19.08	37.71	2.64
	14.458	3.967	−3.630	−2.531	3.109	.853	−.781	−.544	17.21	26.63	−24.01	−22.78
	9.446	1.754	−.883	−3.298	1.782	.331	−.167	−.622	11.16	11.55	−7.09	−27.56
	5.709	3.760	.562	−3.869	1.029	.677	.101	−.697	6.02	18.95	4.34	−27.69
	21.365	4.794	2.627	.376	2.980	.669	.366	.052	19.40	23.02	17.47	3.30
	13.957	4.760	.559	−.579	1.756	.599	.070	−.073	12.12	20.56	3.55	−4.56
	19.669	2.363	1.620	−.184	2.126	.255	.175	−.020	17.18	11.15	10.44	−1.38
	25.111	2.648	1.656	−.567	2.462	.260	.162	−.056	16.96	18.84	9.56	1.57
Average	14.439	3.470	1.355	−1.129	2.372	.570	.223	−.185	15.03	17.76	10.24	−8.88
128	14.085	4.748	2.964	−1.447	4.544	1.532	.956	−.467	20.02	27.69	29.76	−17.86
	11.438	5.270	5.033	.388	3.364	1.550	1.480	.117	14.23	26.37	44.33	5.20
	5.618	3.747	2.372	−1.670	1.387	.925	.586	−.412	6.99	18.75	20.89	−7.51
	17.563	3.434	−3.016	−3.402	3.444	.673	−.591	−.667	20.25	21.29	−20.28	−27.52
	20.155	2.572	1.080	−1.994	3.698	.472	.198	−.366	23.11	15.73	9.06	−18.09
	17.766	7.821	2.800	−2.233	2.889	1.272	.455	−.363	18.25	37.24	21.06	−17.59
	17.731	5.406	3.212	−.135	2.588	.789	.469	−.020	17.41	23.97	23.19	−1.22
	26.835	4.122	2.653	.430	3.388	.520	.335	.054	23.99	18.08	17.04	3.63
	18.449	4.396	−.304	.453	2.133	.508	−.035	.052	15.78	17.49	−1.84	3.61
	17.545	3.939	.985	−.235	1.772	.398	.099	−.024	13.91	16.97	5.68	−2.59
	26.152	.899	4.359	−1.495	2.539	.087	.423	−.145	16.25	3.77	17.65	−8.60
Average	17.576	4.214	2.013	−1.030	2.728	.654	.312	−.160	17.26	20.32	14.13	−8.05
138	14.589	5.663	2.878	1.330	4.559	1.770	.899	.416	19.38	37.58	30.03	16.92
	26.505	5.409	3.402	1.374	6.796	1.387	.872	.352	30.96	34.13	31.11	15.74
	22.863	4.716	2.738	−.162	5.081	1.048	.608	−.036	26.71	29.76	25.04	−1.82
	21.954	2.450	1.511	.247	3.326	.371	.229	.037	22.76	12.69	11.49	2.14
	38.282	2.155	5.994	−.815	5.004	.282	.784	−.107	28.05	9.84	28.35	−5.63
	8.003	2.158	2.869	−.533	1.026	.277	.368	−.068	5.89	9.22	13.52	−3.79
	18.727	5.584	4.115	−.670	2.190	.653	.481	−.078	13.78	23.86	19.40	−4.72
	23.623	5.492	1.140	−.183	2.305	.536	.111	−.018	19.15	17.42	6.25	−1.18
Average	21.818	4.203	3.081	.074	3.328	.641	.470	.011	19.96	20.22	19.50	.64
141	20.434	4.944	2.221	1.510	5.923	1.433	.644	.438	27.14	32.81	23.17	19.21
	25.275	6.045	2.302	.379	6.481	1.550	.590	.097	30.72	38.60	21.86	4.49
	25.093	7.304	1.415	.788	5.283	1.538	.298	.166	28.43	45.49	12.45	8.81
	20.217	3.371	.256	−.329	3.087	.515	.039	−.050	20.96	17.47	1.95	−2.77
	18.714	7.247	4.085	−.689	2.446	.947	.534	−.090	14.58	36.13	20.58	−5.10
	10.013	3.825	2.649	−1.158	1.221	.466	.323	−.141	7.45	16.35	12.66	−7.96
	30.743	8.281	3.515	1.271	2.956	.796	.338	.122	24.92	26.27	19.29	8.30
	30.190	9.005	2.898	2.619	2.648	.790	.254	.230	24.47	28.57	15.90	17.10
Average	22.585	6.253	2.418	.549	3.209	.888	.344	.078	21.21	28.99	15.87	4.69
Group average	18.728	4.451	2.153	−.477	2.881	.685	.331	−.073	18.20	21.60	14.83	−3.18

In discussing the results as summarized in Table 7 it has been thought best to deal first with the general averages for each group and then to proceed to a more detailed examination of the results for the different ages.

The nitrogen balances were positive in all cases. The high-calcium group with a nitrogen intake per unit of weight averaging 4.4 per cent higher than that of the low-calcium group (the reason for which has already been explained, see p. 886), stored on an average 21 per cent more nitrogen per unit of weight than did the low-calcium group. The conclusion which might be reached as to the reason for this is that the protein of the alfalfa is superior for growth purposes to that furnished by ordinary hay supplemented with grain. Other variables enter in, however, such as possible differences in the value of beet pulp and apple pomace, or a possibly favorable effect of the high-calcium intake on protein storage, so that caution should be used in interpreting the result.

TABLE 7.—*Summary of balances by ages in the mineral metabolism experiment, March, 1927, to December, 1929*

HIGH-CALCIUM GROUP

Age and number of trials averaged	Actual intake in grams daily of—				Actual retention in grams daily of—				Intake per 100 pounds live weight in grams daily of—				Retention per 100 pounds live weight in grams daily of—				Retention as percentage of intake				Ratio of Ca to P[a]
	N	Ca	P	Mg	N	Ca	P	Mg	N	Ca	P	Mg	N	Ca	P	Mg	N	Ca	P	Mg	
Under 1 year (average of 13 trials)	89.34	35.04	10.13	11.60	17.93	9.52	4.14	0.81	21.50	8.43	2.44	2.79	4.31	2.29	1.00	0.19	20.07	27.17	40.87	6.98	3.5:1 2.3:1
1 to 2 years (average of 17 trials)	122.92	43.16	12.57	15.78	26.72	7.30	3.20	.22	15.76	5.53	1.61	2.02	3.43	.94	.41	.03	21.74	16.91	25.46	1.39	3.4:1 2.3:1
Over 2 years (average of 9 trials)	161.84	56.73	17.42	21.43	34.08	7.11	3.23	−.80	14.82	5.19	1.60	1.96	3.12	.65	.30	−.07	21.06	12.53	18.54	Nil.	3.3:1 2.2:1
Grand average (39 trials)	120.71	43.59	12.88	15.69	25.49	7.74	3.52	.22	16.53	5.97	1.76	2.15	3.49	1.06	.48	.03	21.10	17.80	27.40	1.40	3.4:1 2.2:1

LOW-CALCIUM GROUP

Under 1 year (average of 13 trials)	80.09	17.22	10.78	7.95	16.78	4.76	2.55	−.12	20.76	4.46	2.79	2.06	4.35	1.24	0.66	−0.03	20.95	27.64	23.65	Nil.	1.6:1 1.9:1
1 to 2 years (average of 17 trials)	109.88	20.15	15.74	11.51	18.93	4.13	1.89	−1.02	15.75	2.89	2.26	1.65	2.71	.59	.27	−.15	17.23	20.50	12.01	Nil.	1.3:1 2.2:1
Over 2 years (average of 7 trials)	128.25	26.57	18.51	14.88	24.72	4.66	2.31	.18	12.52	2.59	1.81	1.45	2.41	.46	.23	.02	19.27	17.54	12.48	1.21	1.4:1 2.0:1
Grand average (37 trials)	102.89	20.61	14.52	10.90	18.73	4.45	2.15	−.48	15.83	3.17	2.23	1.68	2.88	.69	.33	−.07	18.20	21.60	14.80	Nil.	1.4:1 2.1:1

[a] The first set of figures given in each case represents intake; the second, retention.

The calcium balances were positive in all cases. With a calcium intake per unit of weight averaging 88.3 per cent higher than that of the low-calcium group, the high-calcium group stored on an average 53.6 per cent more calcium per unit of weight. Although this group actually stored more calcium than the low-calcium group the percentage retention of that element did not average as high, 17.8 per cent as contrasted with 21.6 per cent.

The phosphorus balances were positive in 72 of the 76 trials. The four negative balances were confined to two heifers, both in the low-calcium group. With a phosphorus intake per unit of weight averaging 21.1 per cent less than that for the low-calcium group, the high-calcium group stored on an average 45.5 per cent more phosphorus per unit of weight, the percentage retention of this element being nearly double that in the low-calcium group, 27.4 per cent as against 14.8 per cent. This finding is perhaps the most interesting one in the whole investigation and its possible significance should not be lost sight of. It will be noted from Table 6 that the ratio of calcium to phosphorus retained is almost the same in both groups, slightly more than 2:1, while the ratio of calcium to phosphorus fed is about two and one-half times as great in the high-calcium group as in the low-calcium group. It would seem from this that the retention ratio is somewhere nearly constant at 2 to 1 irrespective of the ratio in the feed, and it follows in turn that a lowered calcium intake will pull down the phosphorus retention, irrespective of the level of phosphorus fed, to a point where the retention ratio is about 2:1. It would seem, therefore, that a high-calcium content in the ration, even if much above the requirements for that element itself, may be necessary in order to insure adequate storage of phosphorus by growing heifers.[5]

The magnesium balances present a puzzling situation. Forty-eight of the 76 balances determined were negative. These were evenly divided between the two groups, 24 in each, but the individual negative balances averaged somewhat larger in the low-calcium group so that the average result was a slight positive balance in the high-calcium group and a slight negative balance in the low-calcium group.

Similar findings have been noted by other investigators in mineral balance experiments with human subjects and also with cattle, but an entirely satisfactory explanation has never been put forward. Forbes has commented on the situation in several of his papers on mineral metabolism. In one place[6] he remarks that "the interpretation of a negative balance, then, may be a matter of some uncertainty," and in another[7] that—

> balances of mineral nutrients such as magnesium, which are utilized in small proportions of the usual intake, are of much less certain significance, and cannot be closely interpreted—especially in view of the great complication of factors, other than the quantity present, which enter into the determination of the balance of intake to outgo.

Regarding interdependence in the metabolism of this element and that of calcium, referred to earlier in this paper, it appears that where

[5] Since the above was written some unpublished results of other investigators have been brought to the writers' attention which show an apparent independence of calcium and phosphorus in metabolism. These results, however, have been obtained with milking cows. It may be that the situation changes with the advent of lactation.

[6] FORBES, E. B., HUNT, C. H., SCHULTZ, J. A., WINTER, A. B., and REMLER, R. F. THE MINERAL METABOLISM OF THE MILCH COW. Ohio Agr. Expt. Sta. Bul. 363, p. 38.

[7] FORBES, E. B., FRENCH, R. B., and LETONOFF, T. V. THE MINERAL METABOLISM OF THE BEEF STEER. Jour. Nutrition 1: 208. 1929.

the calcium intake was high there was quite a definite and direct interrelationship in the metabolism of these two elements. With a low calcium intake the relationship was not nearly so marked.

Turning to a more detailed study of the results as summarized in Table 6 under the subdivisions of each group according to age, the following points are noted:

(1) As would naturally be expected, intake per unit of weight of all the elements under consideration decreased with increasing age. Most of this decrease took place in the second year as compared with the first, there being in general little further decrease in the third year. The rate of decrease in intake was roughly parallel for both groups and for all elements.

(2) With the single exception of magnesium in the third year, retention per unit of weight also decreased in all cases with increasing

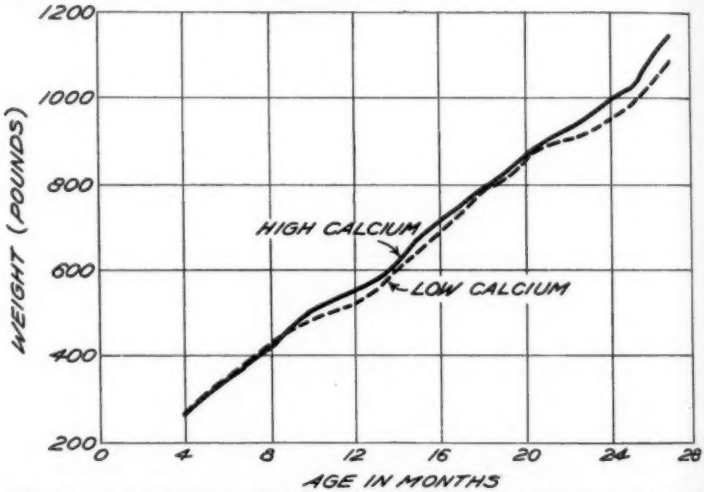

FIGURE 2.—Composite curves representing average weights of heifers in the two groups. The solid line represents the high-calcium and the broken line the low-calcium group

age, and, as with intake, most of the decrease was between the first and second years. Rate of decrease in retention was much higher with calcium and phosphorus than with nitrogen, indicating that the greatest demand for these elements is during the first year of life. Evidently skeletal growth proceeds more rapidly toward completion than does the growth of other body tissues, which contain relatively large amounts of nitrogen and relatively little calcium and phosphorus in their make-up.

Comparing the groups, it is noted that rate of decrease in retention per unit of weight was about the same for phosphorus in both groups; that it was less rapid for nitrogen in the high-calcium group, and less rapid for calcium in the low-calcium group.

(3) Retention of the elements expressed as percentage of intake did not show a uniform decrease with advancing age. Although in general the tendency was to decrease from start to finish, there are several cases of increased percentage retention, notably from the second to the third year, and one case (nitrogen in the high-calcium

group) where percentage retention was higher in the third year than in the first. It is interesting to note that all cases of percentage increase except the one just mentioned were in the low-calcium group, although curiously enough calcium itself was not involved.

In general it can be stated that efficiency in the use of the elements, as measured by relative retention, was lowered with advancing age. This was especially true of the element calcium and of the high-calcium group. A tendency toward an increased efficiency in the third year is probably a reflection of the demands of pregnancy.

The results as a whole point to accumulation of a considerable reserve of all elements by the high-calcium group during the first year of life, with a resultant lowering of relative retention later on. The

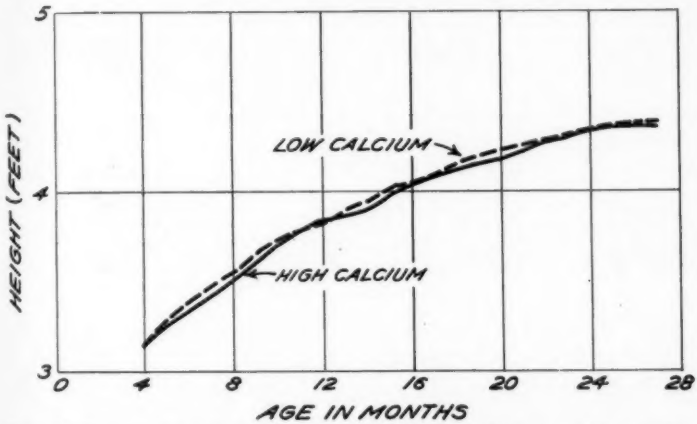

FIGURE 3.—Composite curves representing average heights of heifers in the two groups taken at withers. The solid line represents the high-calcium and the broken line the low-calcium group

low-calcium group, not having accumulated such a large reserve in the earlier stages, must have felt the pinch later on and made an attempt to even matters up, as evidenced by the tendency in this group toward increased efficiency in the third year.

(4) The establishment of approximately a 2 to 1 ratio between amounts of calcium and phosphorus retained irrespective of the ratio in the intake, was very uniform in both groups and at all ages. The significance of this finding has been dealt with rather fully under the discussion of average results (p. 891). The striking uniformity at all ages is additional confirmation of the conclusions there drawn.

GROWTH RECORDS OF THE ANIMALS

All the heifers were weighed and measured twice a month until they were a year old. After that the records were taken once a month. The measurements recorded were height at withers and heart girth. Photographs were also taken from time to time. A graphic summary of the growth records is shown in Figures 2, 3, and 4.

These charts need little comment. The lower weight of the low-calcium group from the twenty-first month onwards is due largely to the fact that on an average they were bred about one month later

than the other group, and the difference is due to the earlier stage of gestation. It will be noted that their weights at any given age after 21 months are almost identical with those of the other group one month earlier. Height and girth remained about the same in both groups all through the experiment. Photographs taken when the heifers were 2 years old appear in Figures 5 and 6. In addition a record of the weight and condition at birth of each heifer's first calf appears in Table 8. Two calves in each group were sired by one bull and the other two in each group by his son, so that influence of sire was evenly distributed.

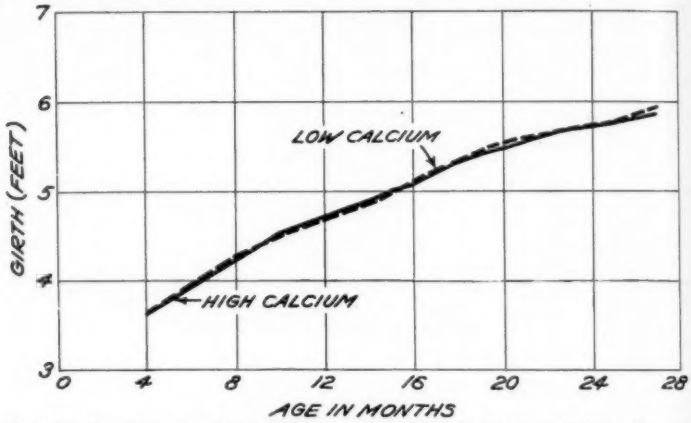

FIGURE 4.—Composite curves representing the average heart girths of heifers in the two groups. The solid line represents the high-calcium and the broken line the low-calcium group

TABLE 8.—*Weight and condition at birth of calves born to heifers in both calcium groups*

Calf of heifer No.	High calcium		Calf of heifer No.	Low calcium	
	Weight at birth	Condition at birth		Weight at birth	Condition at birth
	Pounds			*Pounds*	
121	85	Excellent.	126	78	Good.
131	80	Good.	128	90	Do.
137	75	Do.	138	75	Do.
139	85	Do.	141	97	Excellent.
Average	81		Average	85	

It would seem from a study of the growth records and from close observation of the animals that thus far at least the considerably lower mineral storage by the low-calcium group has had no ill effects. It would be interesting to know what the heifers in the high-calcium group have done with the extra calcium and phosphorus they have stored. Presumably it has been stored as a reserve in the bones. Time alone will tell whether this large reserve is necessary in order to tide the animals over periods of strain and possible mineral shortage during heavy lactation. If it is found that the low-calcium group continues to produce and reproduce normally then it would seem reasonable to conclude that heifers can make satisfactory growth on

rations supplying approximately 4.5 gm. of calcium daily during the first year of life, 3 gm. daily during the second year, and 2.5 gm. daily during the third year for each 100 pounds of live weight.

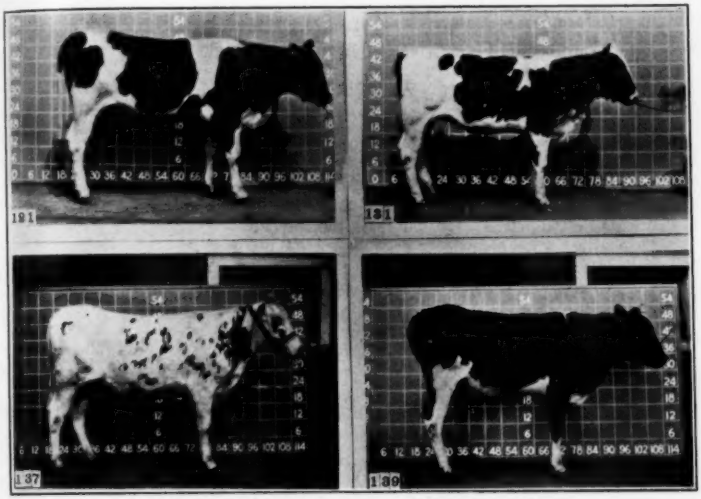

FIGURE 5.—The high-calcium group of heifers at 2 years of age

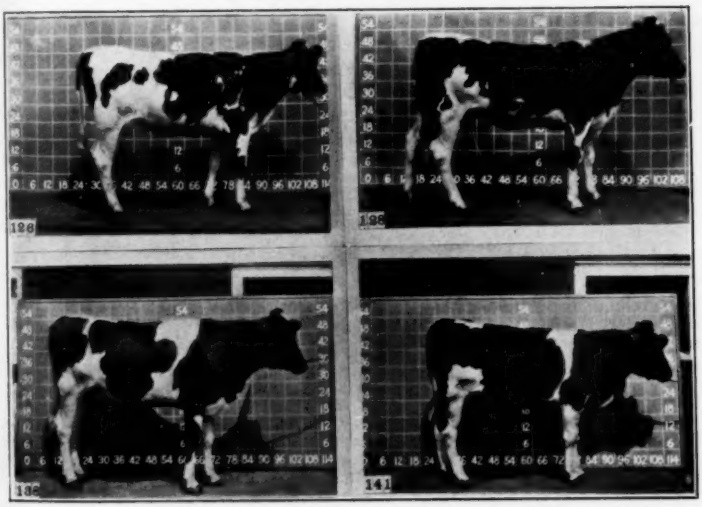

FIGURE 6.—The low-calcium group of heifers at 2 years of age

Good-quality hay from the mixed grasses will supply the lesser amounts (2.5–3 gm. daily); rowen,[8] legume hay, or a mixture of legume and grass hay will assure the larger amount (4.5 gm. daily).

[8] "Rowen" is a New England term applied to second-crop hay, usually restricted to hay from the grasses. It is used in this sense here.

Whether heifers could make good growth on rations containing smaller amounts of calcium than these rations supplied is still an open question. The one fact which has been strikingly demonstrated is the interdependence in the metabolism of calcium and phosphorus in these growing animals. The investigation is being continued with the requirements for phosphorus as the objective.

SUMMARY

The calcium requirements of two groups of dairy heifers were studied during the first three years of life. One group was fed a high-calcium and the other a low-calcium ration.

The nitrogen balances were uniformly positive and no very definite conclusions regarding them seem justifiable.

The calcium balances were all positive, animals in the high-calcium group averaging 53.6 per cent greater storage, per unit of weight, than those in the low-calcium group; the former averaged 88.3 per cent higher calcium intake, per unit of weight, than the latter. The percentage retention of calcium by the high-calcium group was, however, only 17.8 as compared to 21.6 per cent for the low-calcium group.

The phosphorus balance was positive in 72 out of 76 trials. The high-calcium group stored on an average 45.5 per cent more phosphorus, per unit of weight, than the low-calcium group; this was done on a phosphorus intake of 21.1 per cent less, per unit of weight. The high-calcium group also retained 27.4 per cent phosphorus as against 14.8 per cent for the low-calcium group. It appeared that a high calcium content in the ration was necessary to insure adequate phosphorus storage by growing heifers.

The magnesium balances were negative in 48 out of the 76 trials, 24 of these negatives occurring in the high-calcium and the same number in the low-calcium groups. Individual negative balances averaged somewhat larger in the low-calcium group, hence the average result was a slight positive balance in the high-calcium and a slight negative balance in the low-calcium group as a whole.

The intake per unit of weight of all elements decreased with increasing age, and retention per unit of weight nearly always decreased in a similar manner. The retention of elements when expressed as percentage of intake did not show a uniform decrease with advancing age. The results as a whole indicate an accumulation of a considerable reserve of all elements by the high-calcium group in the first year of life. The retention of the 2 to 1 ratio between the amounts of calcium and phosphorus retained, irrespective of the ratio in the intake, was very uniform in both groups and at all ages.

A study of the growth records of the animals, and careful observations of the animals themselves, indicate that, thus far at least, the considerably lower mineral storage by the low-calcium group had no ill effects.

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